In Situ Fabrication Technologies: Meeting the Challenge for Exploration

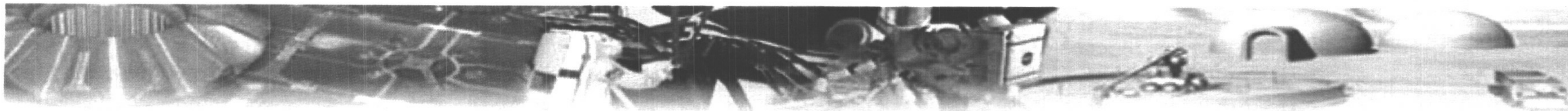
Presentation for the National Space and Missile Materials Symposium

Summerlin, Nevada

June 27- July 1, 2005

Presenter: Richard W. Howard / Teledyne Brown Engineering
for
Marshall Space Flight Center

Explore. Discover. Understand.

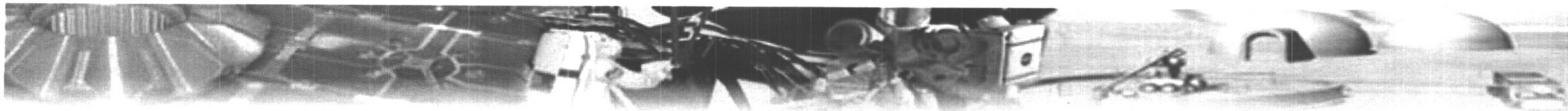


SSPO

Lunar & Martian Fabrication Technologies Development Overview

- Exploration Vision
- Vision Requirements Early in the Program
- Vision Requirements Today
- Why is ISFR Technology Needed?
- ISFR and In Situ Resource Utilization (ISRU)
- Fabrication Feedstock Considerations
- Planetary Resource Primer
- Average Chemical Element Abundances in Lunar Soil
- Chemical Elements in Aerospace Engineering Materials
- Schematic of Raw Regolith Processing into Constituent Components
- Iron, Aluminum, and Basalt Processing from Separated Elements and Compounds
- Space Power Systems
- Power Source Applicability

- Fabrication Systems Technologies
- Repair and Nondestructive Evaluation (NDE)
- Habitat Structures



Exploration Vision

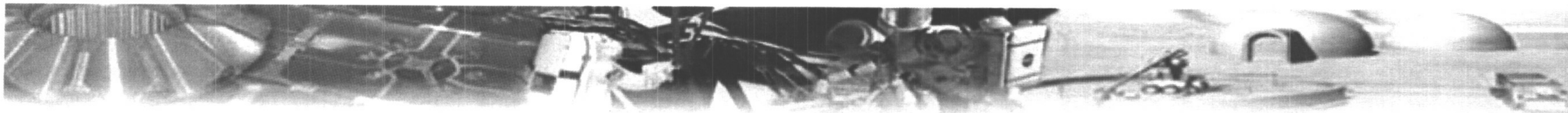
President George Bush on January 14, 2004 issued his vision for U.S. Space Exploration with the Goals and Objectives to:

- **Implement a sustained and affordable human and robotic program to explore the solar system and beyond**

- **Extend human presence across the solar system, starting with a human return to the moon by 2020, in preparation for human exploration of Mars and other destinations**

- **Develop the innovative technologies, knowledge, and infrastructure both to explore and to support decisions about the destinations for human exploration**

- **Promote international and commercial participation to further U.S. scientific, security, and economic interests.**



Vision Requirements Early in the Program

- The In Situ Fabrication and Repair (ISFR) element, as part of the Human System Research & Technology Development Program, was established as NASA moved to align with the President's vision.

- The ISFR element is comprised of three sub-elements: *Fabrication Systems Technologies; Repair and Nondestructive Evaluation; and Habitat Structures.*

- This group began working with early concepts of operations and roadmap documents and used these as a requirements 'push' up to NASA Headquarters for incorporation into the Exploration Requirements documentation. Used as early guidance were:

- *The Operations Concept Document for Human Exploration of Mars (OCDHEM)*
  - Vehicle Autonomy and Automation
  - In-Flight Maintenance
  - New Technologies for Surface Operations
  - Mission Logistics
  - Contingency Maintenance and Repair
  - Planetary Surface Operations
  - General Maintenance including pre-deployment of resources

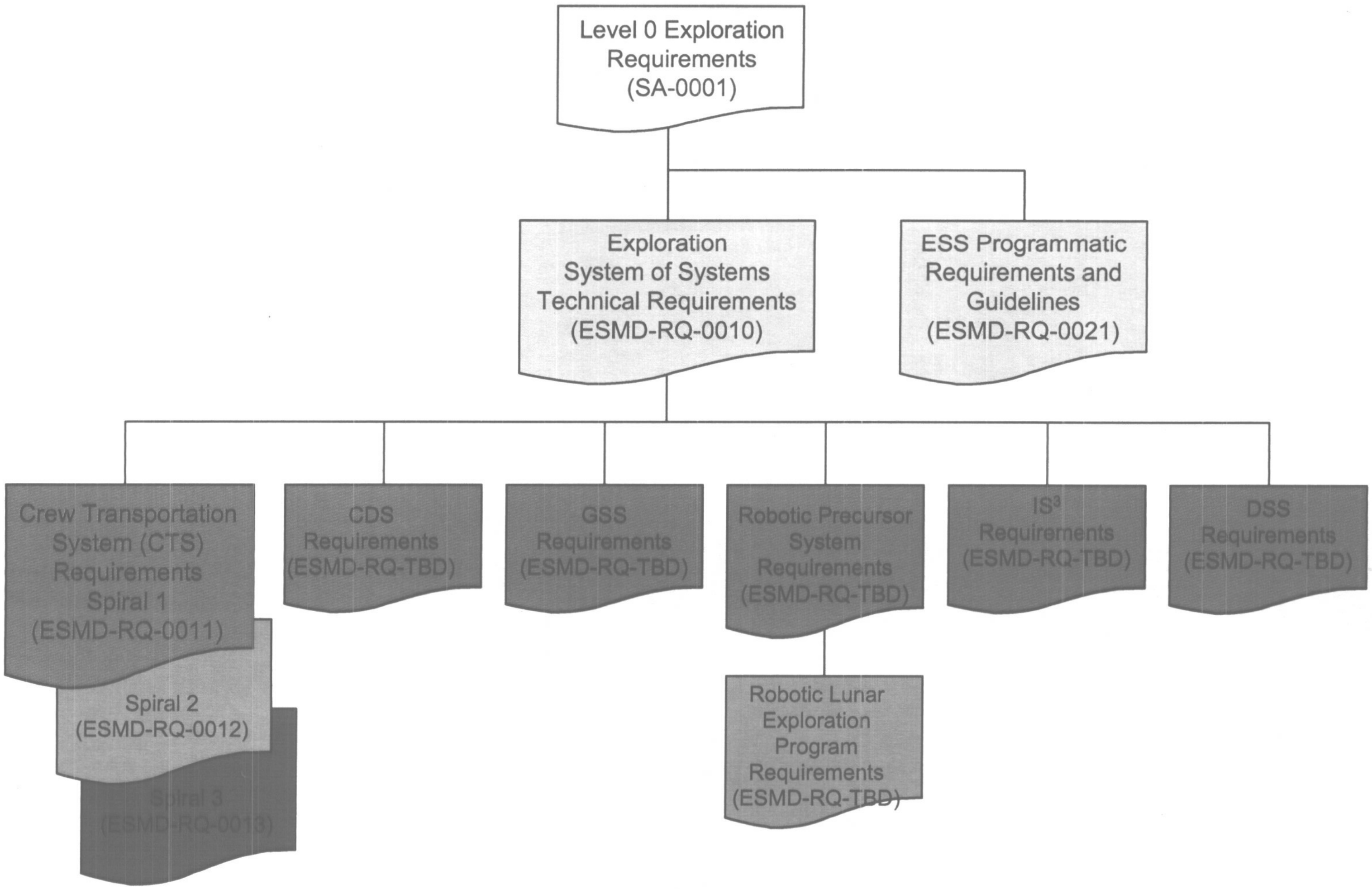
- *The Bioastronautics Roadmap*
  - Radiation shielding for the crew either in transit or in conjunction with habitat
  - Maintainable advanced life support for long duration missions
  - Human factors considerations including use of tele-robotic operations

SSPO

Vision Requirements Today

Requirements are now starting to mature from NASA Headquarters

The Vision for Space - Document Tree
(partial)



SSPO

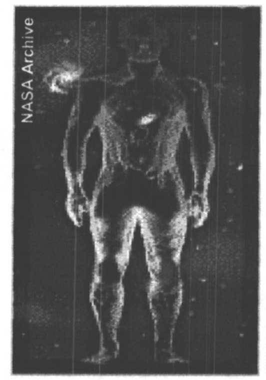
Why is ISFR Technology Needed?

- Longer duration missions without near access to Earth will require increased maintainability of systems
- *Component degradation and failure is inevitable*
- The Space Architect has identified sparing as a principal issue for reducing the mass required for long duration exploration missions
- *It would not be practical to carry a complete spare parts and tools inventory, nor would an extensive collection of spares necessarily fulfill every emergency need*
- Fabrication of new tools *in situ* to cover unforeseen needs will significantly mitigate risk
- Fabrication equipment used for components, parts, and tools can also be used for electronic or biological applications (with proper cleanliness and sterility observed)
- Humans living in reduced gravity and harsh environment for extended periods of time must be able to act autonomously for their survival
- Additional potential for crew injuries requires new medical techniques
- As the distance between Mission location and Earth increases, risk increases, and advanced tool suite will help mitigate some of these

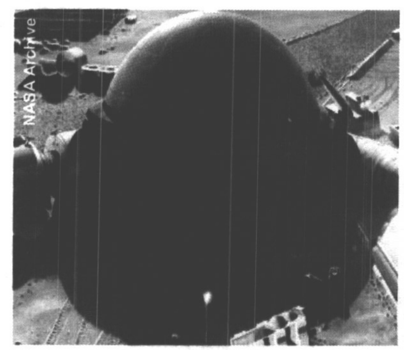
SSPO

ISFR and In Situ Resource Utilization (ISRU)

- In-Situ Fabrication and Repair (ISFR)
  - Fabrication Systems Technologies
    - Metals, Plastics, Ceramics, and Composites
    - Medical Products
    - Bioplotter
  - Repair and NDE Technologies
  - Habitat Structures
  - Baseline Concept for ISFR uses provisioned feedstocks
  - Utilize ISRU "mined and refined" capability as it matures



- In-Situ Resource Utilization (ISRU)
  - Maximize the use of natural resources through the extraction from and/or transformation of Lunar and Martian regoliths
  - Provide many of the needed ISFR feed-stocks for fabrication processes including
    - Silicon
    - Iron, aluminum, titanium
    - Glass/Ceramics
  - Recycling

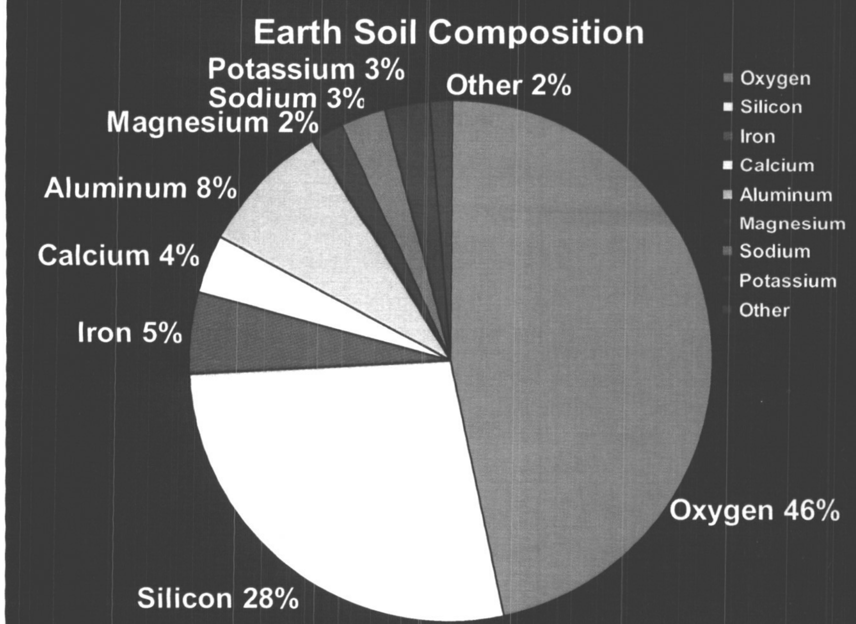


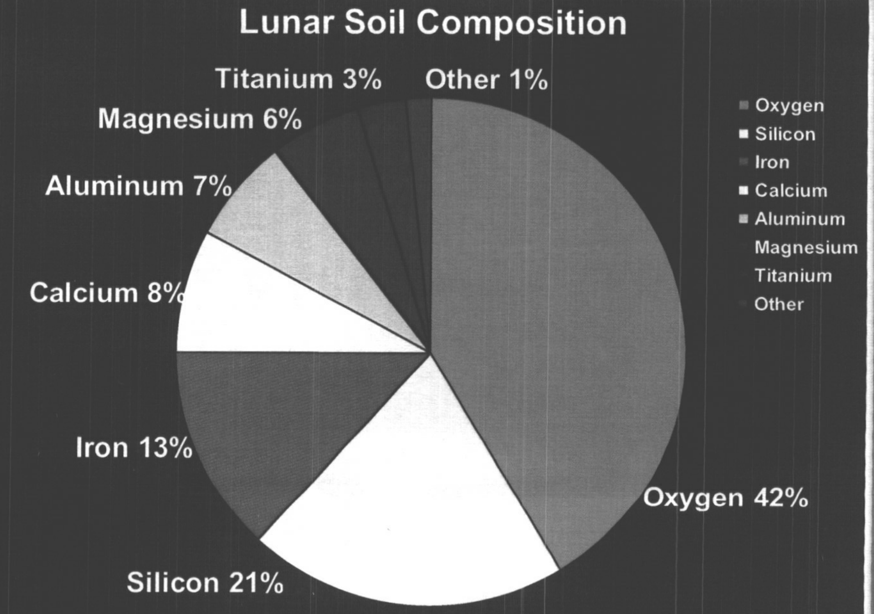
SSPO

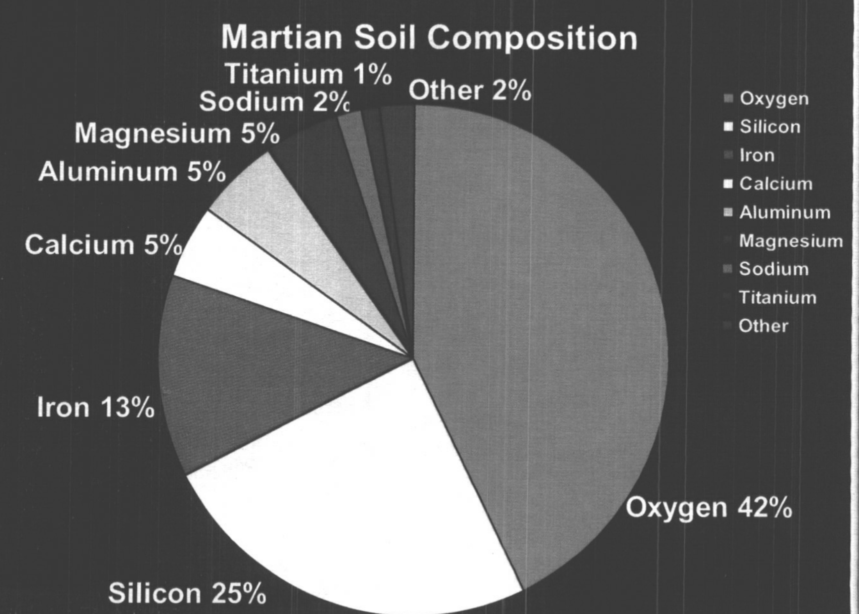
Fabrication Feedstock Considerations

- Feedstock quantities required
- Form required: fine powders; engineered shapes such as bars, rod, plate; filaments
- Pedigree of feedstocks: purity of powders, chemical and physical analysis
- Compatibility with micro-G or hypo-G fabrication
- Ability to recycle back into new feedstock
- Mission compatible with existing hardware
- Number of feedstocks types required – should be minimized
- Shifting from supplied feedstocks to in situ resources must be process compatible
- Infrastructure required to process adequate quantities of regolith into usable feedstocks (power, structure, chemicals, retorts and vessels)
- Economics and logistics of 'make or bring' feedstocks

Planetary Resource Primer







SSPO

Average Chemical Element Abundances in Lunar Soil

Element	Abundance	Element	Abundance	Element	Abundance	Element	Abundance
Al	6.80%	Bi	3.19 ppb	Ho	3.73 ppm	Ru	0.231 ppm
Ca	7.88%	Br	0.178 ppm	I	2.00 ppb	Sb	22.1 ppb
Cr	0.26%	C	104 ppm	In	32.9 ppb	Sc	48.8 ppm
Fe	13.20%	Cd	0.197 ppm	Ir	6.32 ppb	Se	0.306 ppm
K	0.11%	Ce	48.8 ppm	La	17.2 ppm	Sm	10.9 ppm
Mg	5.76%	Cl	25.6 ppm	Li	12.9 ppm	Sn	0.900 ppm
Mn	0.17%	Co	40.3 ppm	Lu	1.22 ppm	Sr	167 ppm
Na	0.29%	Cs	0.392 ppm	Mo	0.520 ppm	Ta	1.26 ppm
O	41.30%	Cu	14.4 ppm	N	95.4 ppm	Tb	2.58 ppm
P	0.07%	Dy	15.3 ppm	Nb	19.6 ppm	Te	0.0545 ppm
S	0.13%	Er	19.24 ppm	Nd	38.2 ppm	Th	2.50 ppm
Si	20.40%	Eu	1.77 ppm	Ne	2.75 ppm	Tl	1.61 ppb
Ti	3.10%	F	174 ppm	Ni	169 ppm	Tm	1.42 ppm
Ag	45.2 ppb	Ga	4.99 ppm	Os	12.9 ppb	U	0.805 ppm
Ar	0.800 ppm	Gd	14.3 ppm	Pb	3.11 ppm	V	114 ppm
As	0.206 ppm	Ge	0.626 ppm	Pd	12.3 ppb	W	0.358 ppm
Au	2.66 ppb	H	54.8 ppm	Pr	7.20 ppm	Y	84.2 ppm
B	4.78 ppm	He	28.5 ppm	Rb	3.21 ppm	Yb	8.40 ppm
Ba	195 ppm	Hf	7.77 ppm	Re	1.36 ppb	Zn	23.4 ppm
Be	2.63 ppm	Hg	0.019 ppm	Rh	0.192 ppm	Zr	311 ppm

SSPO

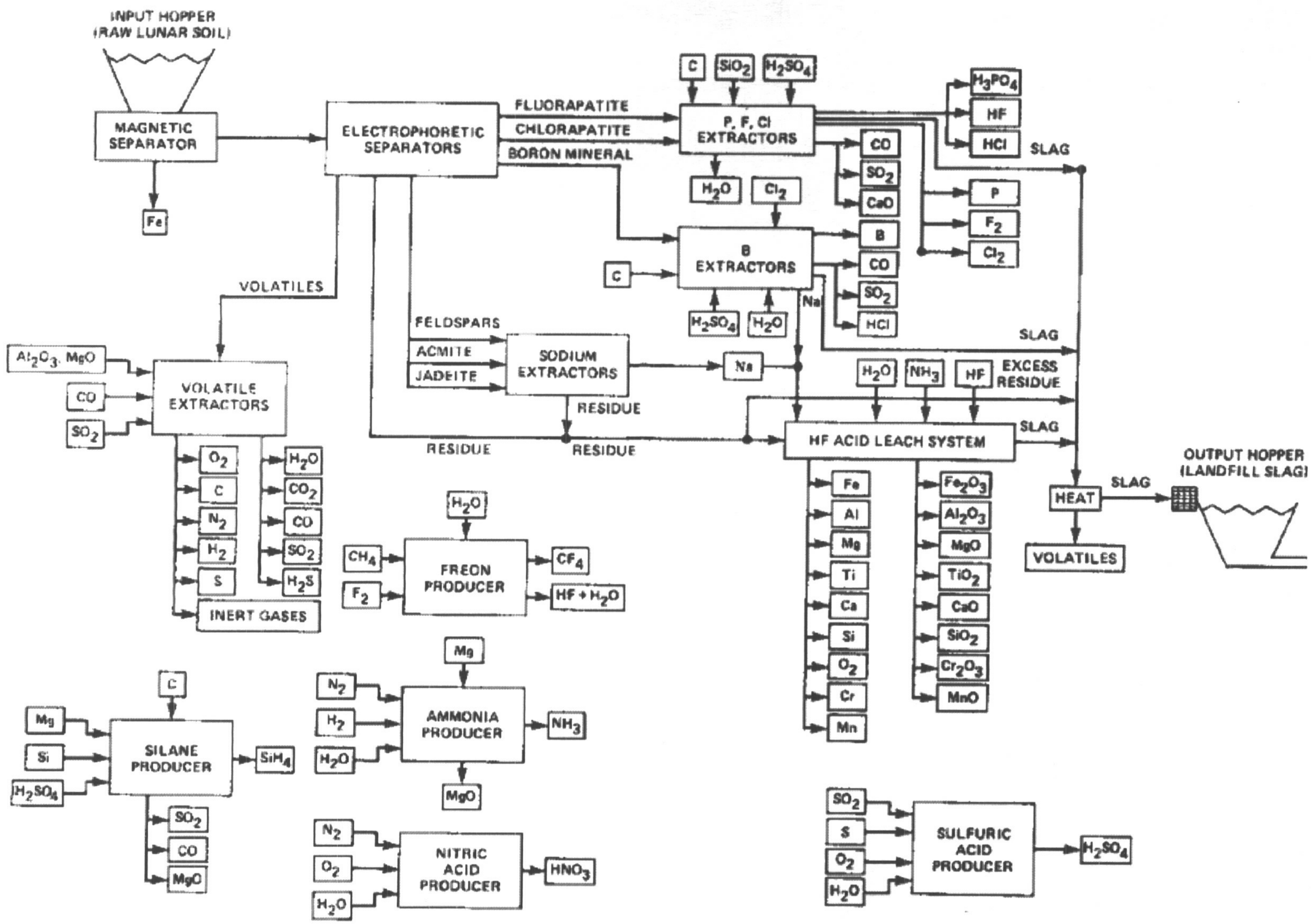
Chemical Elements in Aerospace Engineering

Materials

Elements	Aluminum Alloys	Stainless-Steel Alloys	Nickel Alloys	Refractory Metals	Cement	Titanium Alloys	Ceramics
Al	X		X		X	X	X
B		X					
Be							X
Bi	X						
C		X	X				
Ca					X		
Co			X				
Cr	X	X	X				
Cu	X		X				
Fe	X	X	X		X		
Ge				X			
Hf				X			
K					X		
Mg	X				X		
Mn	X	X	X				
Mo			X	X			
Na					X		
Nb			X	X			
Ni			X				
O							X
P		X	X				
S		X	X		X		
Si	X	X			X		X
Ta			X	X			
Ti	X		X			X	
V	X					X	
W				X			
Zn	X						
Zr	X			X			

SSPO

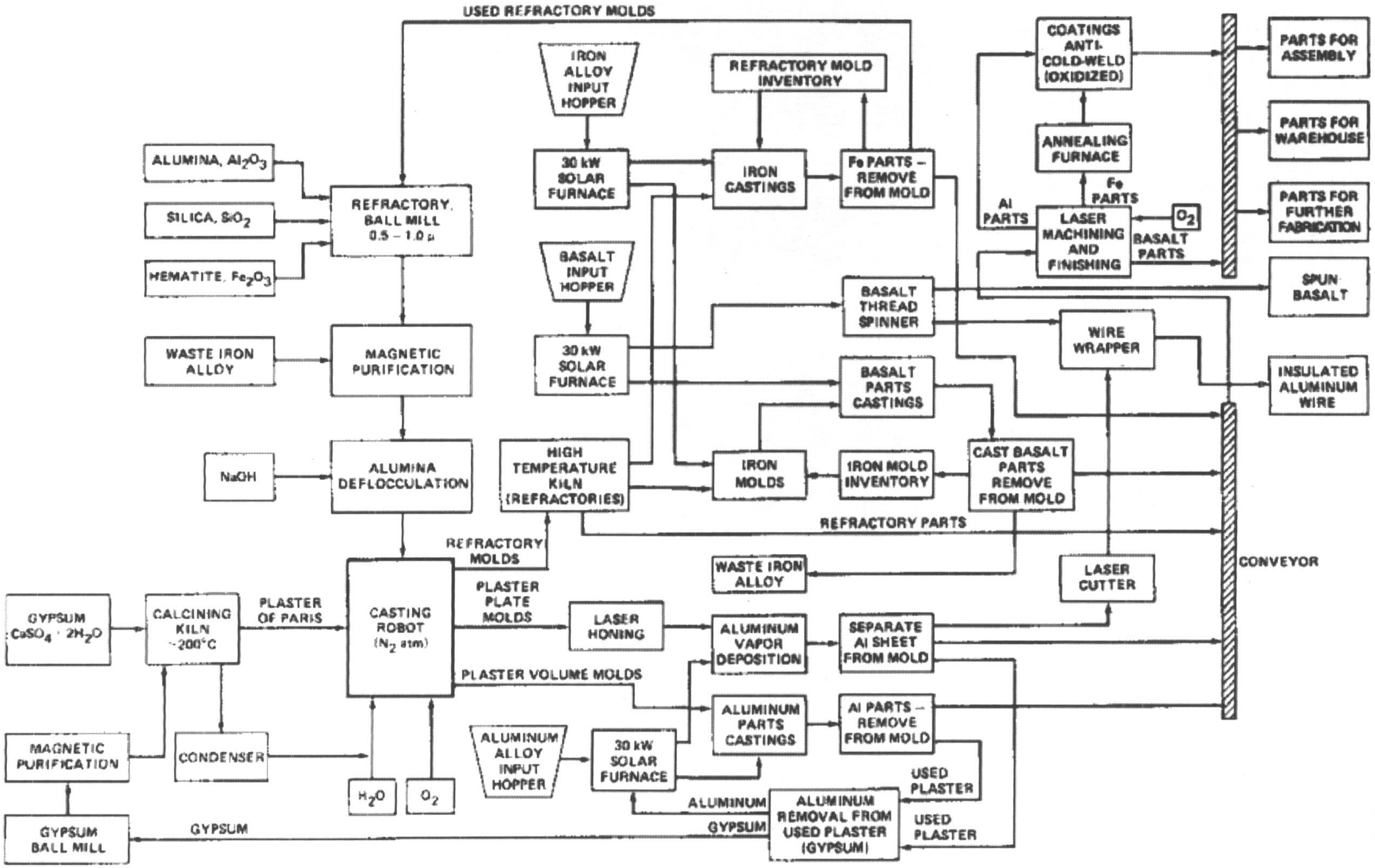
Schematic of Raw Regolith Processing into Constituent Components



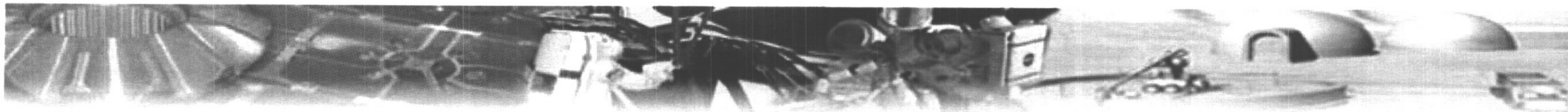
From the Proceedings of the 1980 NASA/ASEE Summer Study
NASA Conference Publication 2255

SSPO

Iron, Aluminum, and Basalt Processing from Separated Elements and Compounds



From the Proceedings of the 1980 NASA/ASEE Summer Study
NASA Conference Publication 2255



Space Power Systems

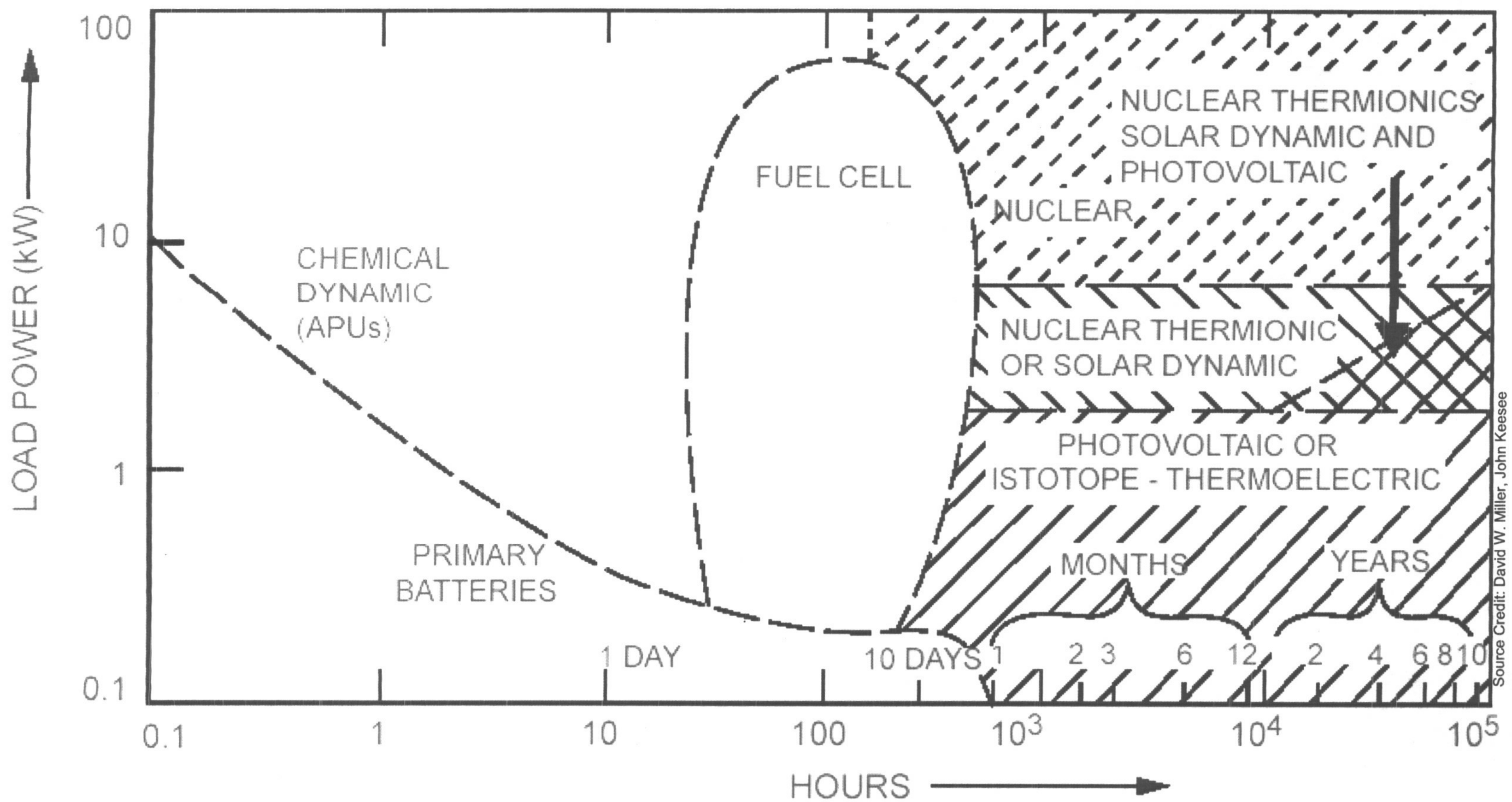
- Transport of fabrication systems implies transport of power systems capable of supplying adequate power to the fabricators.
- Mass and volume of whole system (fabricator, power, feedstock) must be traded against mission requirements, vehicle capability, redundant systems, carrying spares only)

Categories of Space Power Systems

Primary Batteries	Secondary Battery
Photovoltaic	Flywheel Storage
Thermionic Converter	Thermoelectric Converter
Regenerative Fuel Cell	Fuel Cell
Chemical Dynamic	Solar Dynamic
Nuclear	Radioisotope
Electrodynamic Tethers	Propulsion-Charged Tethers

SSPO

Power Source Applicability



Approximate ranges of application of different power sources.

SSPO

Lunar & Martian Fabrication Systems Technologies Development Overview

- Fabrication Systems Technologies
- Fabrication Trade Study – Applications
- Technologies Examined
- Trade Study - Capabilities Summary
- Trade Study Results For Multi-Material Fabricator
- Trade Study - Capabilities Summary
- Trade Study Top Technologies for Processing of Metals, Plastics, Ceramics & Composites
- Fabrication Technology Summary
- Trade Study Rankings For Electronics Fabricator
- Trade Study - Recommendation For Electronics Fabricator
- Biological Fabricators - Medical Products
- Biological Fabricators - Bioplotter (Tissue Printing)
- Trade Study - Recommendation For Biological Fabricator
- Fabrication Systems Gaps
- Fabrication Technology Performance Validation Test Plan

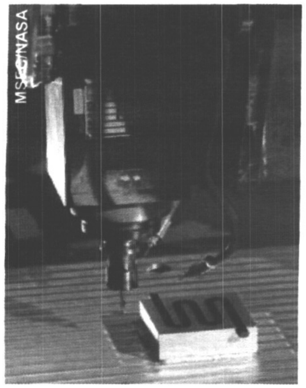
Fabrication Systems Technologies

- ISFR-Fabrication Systems Technologies Sub-element Purpose
  - Fabricate On-orbit Replacement or Unforeseen Parts
    - ISS, Moon, and Mars missions will benefit from capabilities
    - Reduced sparing possible by component vs. Orbital Replacement Units
    - Rectify design inadequacies that may result from off-nominal scenarios
    - Layered manufacturing techniques may enable unique geometries such as internal cavities or cooling passages as well as future functional gradient materials.
  - Fabricate On-orbit Replacement Electronic Parts
    - Provide Printed Circuit Board (PCB) and embedded electronics capabilities
    - Focus on planar circuitry equivalents for discrete components fabricated on provisioned or fabricated substrates to enable complete PCB replacement
  - Fabricate On-orbit Replacement Medical Devices or Biological Constructs
    - Invasive: pins, plates, stints, catheters, sutures, surgical tools and dental instruments, adhesives for tissue binding and affixing implants
    - Non-invasive: casts, orthodics, tubes, syringes, gloves
    - Dental: fillings, crowns, bridges, dental cement
    - Print viable human tissue on hydrogel or collagen scaffolds

SSPO

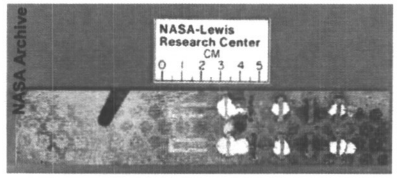
Fabrication Trade Study - Applications

Metals



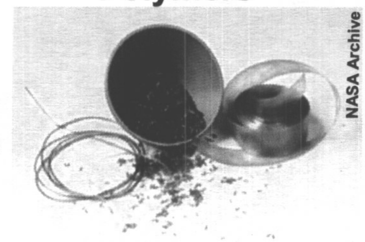
- Aluminum Alloys
- Titanium Alloys
- Stainless Steels
- Superalloys
- Others TBD

Composites



Polymers

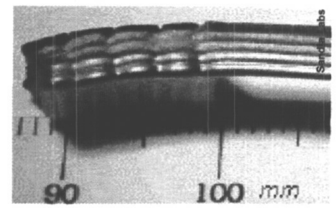
- ABS Plastic
- Elastomers
- Polycarbonate
- Polyphenyl Sulfone
- Others TBD



ISFR-Fabrication

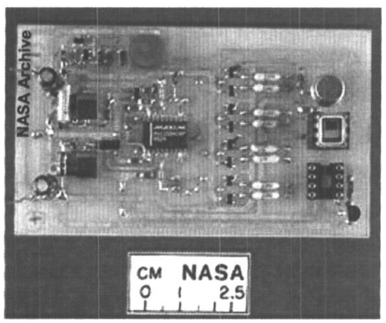
- Moon & Mars Surface Products
  - Replacement Parts
  - Unforeseen Tools
- Conformal Repair Patches
  - Habitat Fittings
  - ECLS Parts
- Electronic Components
  - ElastomerSeals

Functional Gradient Materials



Functional Gradient
Silicon Nitride to Tungsten

Electronics



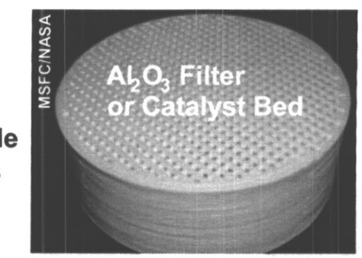
- PC Boards
- Discrete Components
- Crew Displays
- Area Lighting

Trade Study of Processes:
Additive, Subtractive, Hybrid

- Three Dimensional Printing
- Computer Numerical Control
- Direct Metal Process
- Electron Beam Freeform Fabrication
- Electron Beam Melting
- Fused Deposition Modeling
- Kinetic Metallization
- Laser Engineered Net Shaping
- Laminated Object Manufacturing
- Precision Metal Deposition
- Stereolithography
- Selective Inhibition of Sintering
- Selective Laser Melting
- Selective Laser Sintering
- Ultrasonic Consolidation
- Casting Methods ...
- Plasma Spray, Chemical Vapor Deposition, etc.

Ceramics

- Alumina
- Zirconia
- Silica
- Silicon Nitride
- Misc. Oxides
- Others TBD



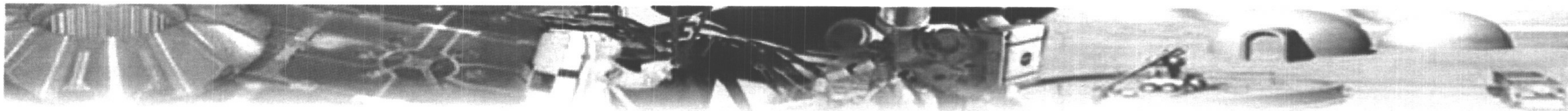
← Manufacturing Processes →

← Products →

Fabricated From:

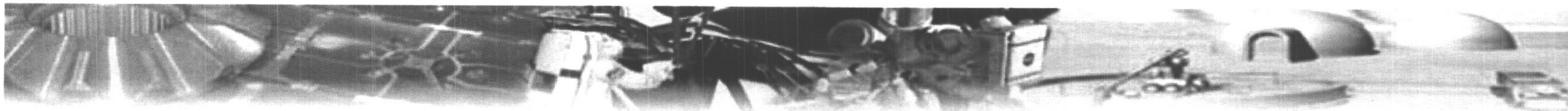
- Metals
- Plastics
- Composites
- Ceramics
- Electronic
- Biological

SSPO



Technologies Examined

Acronym or Process	Process or System Description
Additive Technologies	
3DP: Z-Corp	3-Dimensional Printing: Vendor, Z-Corp
3DP: Prometal	3-Dimensional Printing: Vendor, Prometal
Bioplotter	3-Dimensional Printing for Biological Constructs
CVD	Chemical Vapor Deposition
DMP	Direct Metal Process
EBF^3	Electron Beam Freeform Fabrication
EBM:Arcam	Electron Beam Melting: Vendor, Arcam
EPMD	Electronic Parts Material Deposition
FDM	Fused Deposition Modeling
KM	Kinetic Metallization
LENS	Laser Engineered Net Shaping
LOM	Laminated Object Manufacturing
MELATO	Metal Laminated Tooling (hybrid system, includes CNC milling)
PAS	Plasma Arc Spray
Photolithography	Process for printing PC board circuits
PMD	Precision Metal Deposition
Robocasting	Sandia Labs Slurry Extrusion Process (hybrid system, includes CNC milling)
RSP	Rapid Solidification Process



Technologies Examined

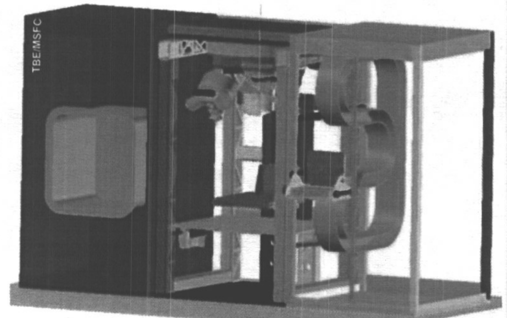
Acronym or Process	Process or System Description
Additive Technologies (cont'd)	
SLA	Stereolithography
SIS	Selective Inhibition of Sintering
SLM	Selective Laser Melting
SLS: 3D Systems	Selective Laser Sintering: Vendor, 3D Systems
SLS: EOS	Selective Laser Sintering: Vendor, EOS
UC	Ultrasonic Consolidation (hybrid system, includes CNC milling)
Subtractive Technologies	
CNC Machining	Computer Numerical Controlled Machining (both milling and lathe operations)
EDM	Electrical Discharge Machining
EPMM	Electrical Parts Material Machining
Other Methods	
Casting, Formative Methods	Methods for Casting Materials Into Net Shape
Cold Forming	Various Techniques for Working Ambient Materials
Die Casting	Various Techniques for Materials Casting
Hot Forming	Various Techniques for Working Heated Materials

SSPO

Trade Study - Capabilities Summary

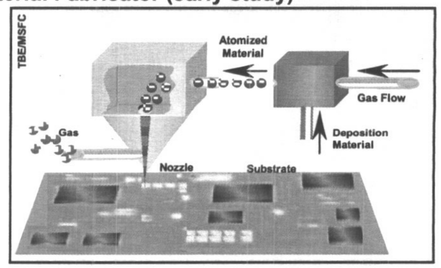
SSPO

- Multi- Material Fabricator
  - Spirals 3, 4, 5: Crew tended in pressurized cabin
  - Fabricate tools, parts and structural components using provisioned, recycled and refined in situ resources (up to 18" per side in size) resources



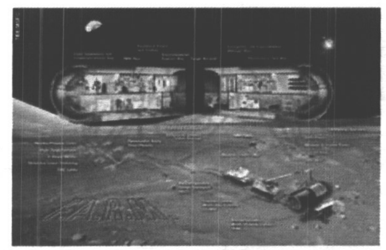
Multi- Material Fabricator (early study)

- Electronics Fabricator (preliminary assessment)
  - Spirals 3, 4, 5: Crew tended in pressurized cabin
  - Fabricate PC boards as well as electronic components using provisioned, recycled and refined in situ resources



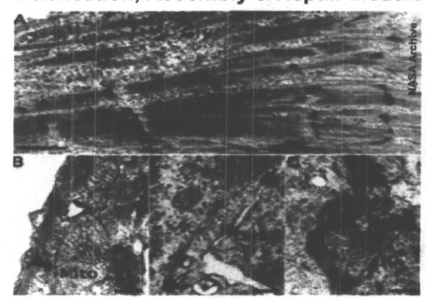
Electronics Material Deposition

- Fabrication, Assembly & Repair Module (preliminary assessment for information only)
  - Spirals 3, 4, 5: Crew tended in pressurized cabin
  - Fabricate tools, parts, structural components and electronics using provisioned, recycled, and refined in situ resources



Fabrication, Assembly & Repair Module

- Biological Tissue Printing (preliminary assessment for information only)
  - Spirals 3, 4, 5: Crew tended in pressurized cabin
  - Fabricate tissue constructs by culturing cells on growth substrates using provisioned, recycled, and refined resources



Micrograph of Printed Heart Tissue

Trade Study Results For Multi-Material Fabricator

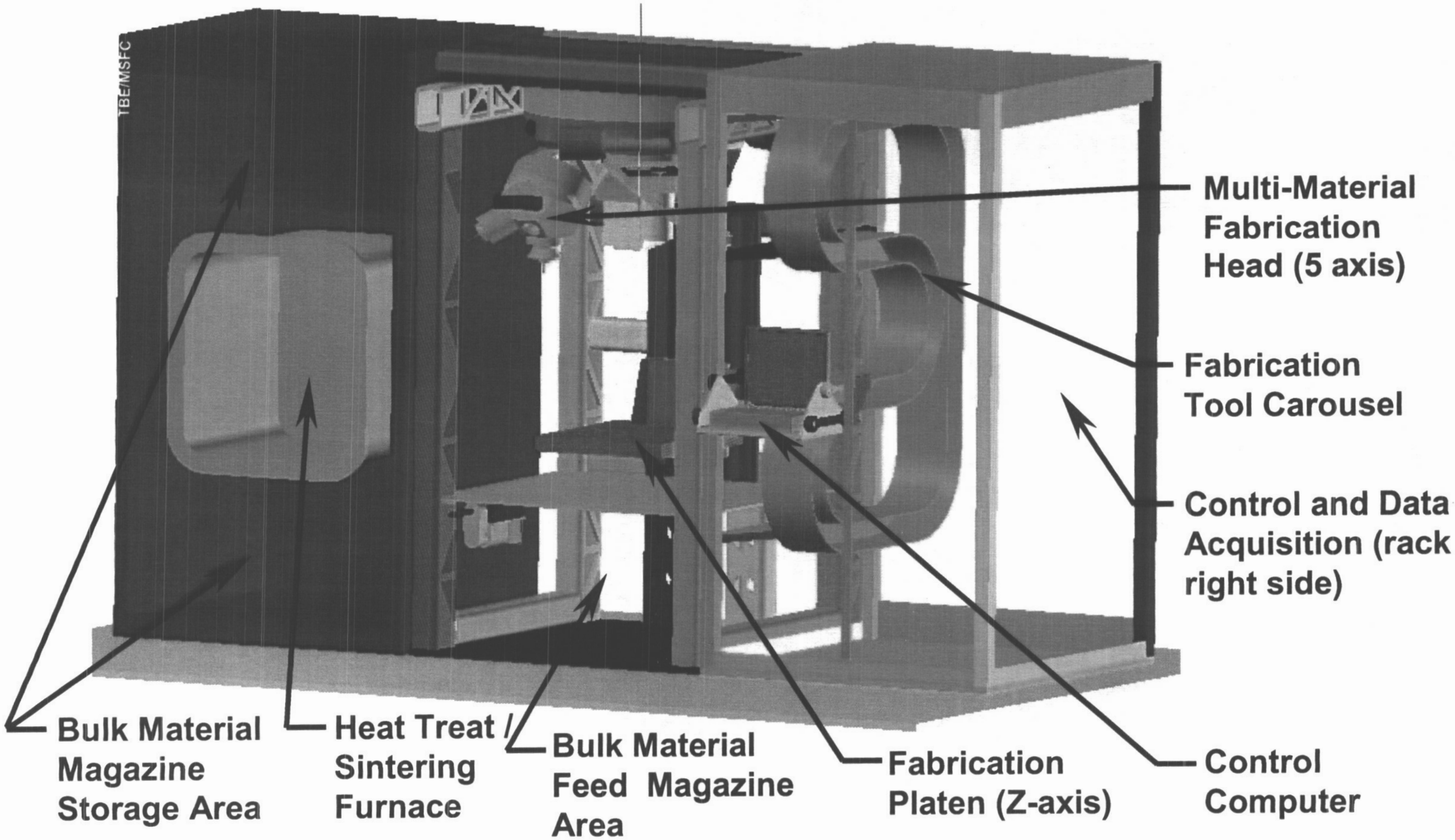
- Hybrid architecture recommended to achieve performance while minimizing gap closure efforts
  - Utilize CNC machining as baseline since it requires least gap closure, can provide finishing for other processes, and partial gravity effects will be minimal
  - Utilize additive methods to minimize feedstock mass as well as support complex geometries and advanced capabilities such as functional gradient materials or internal cavities
  - Remove electronics and biological functions from main fabricator

- Potential hybrid groupings should be investigated in follow-on architecture study
  - Groupings of technologies not analyzed in initial trade study other than as available hybrid units with integral CNC
  - Investigate groupings of integral multiple end-effectors arrangement or of interchangeable end-effectors

SSPO

Trade Study - Capabilities Summary

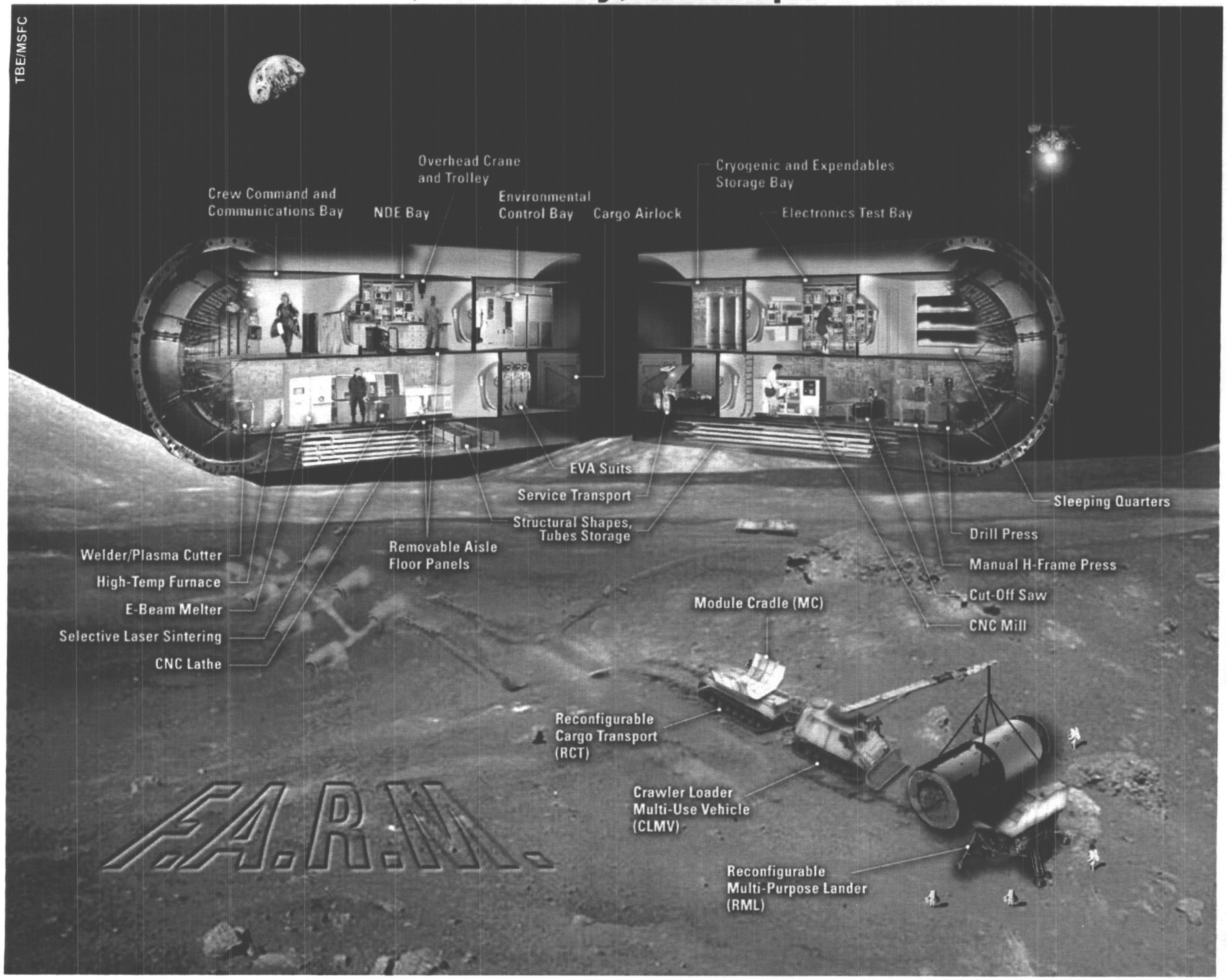
Early Concept for a Multi- Material Fabricator Ground Unit (Processing, Metals, Plastics, Ceramics, & Composites)



SSPO

Trade Study - Capabilities Summary

Fabrication, Assembly, and Repair Module



SSPO

Trade Study Top Technologies for Processing of Metals, Plastics, Ceramics & Composites

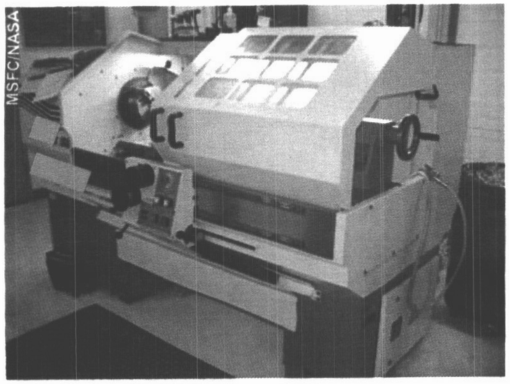
- **Top 9 Ranked Technologies Are Shown Below For Processing of Metals, Plastics, Ceramics and Composites**

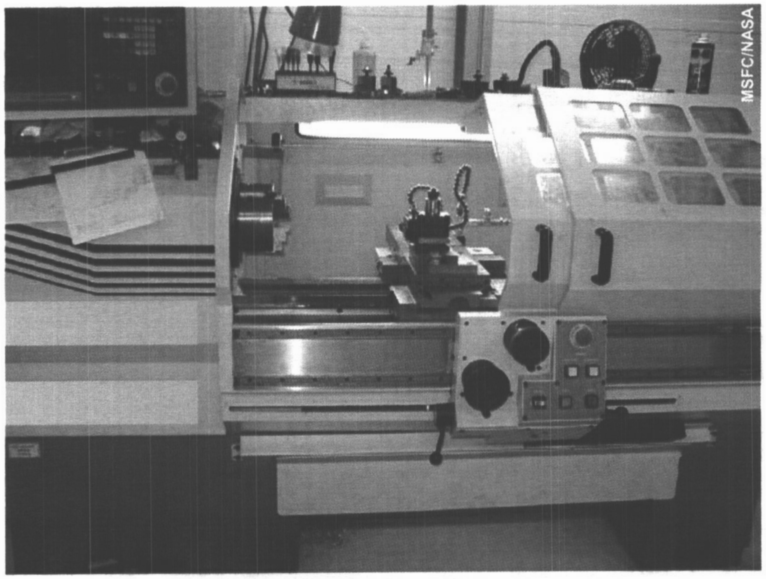
Technology
CNC Machining
Ultrasonic Object Consolidation
Robocasting
Fused Deposition Modeling
Selective Laser Sintering
Selective Laser Melting
Casting Methods
3D Printing, Generic

- **Separation of Electronics and Biological Tissue Fabrication Is Assumed Due to Feature Size Differences and Contamination Control Issues**

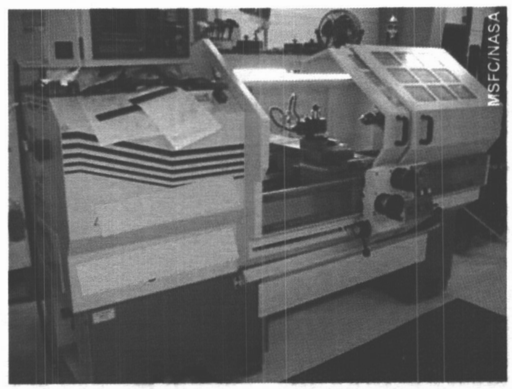
Fabrication Technology Summary

Computer Numerical Controlled Machining



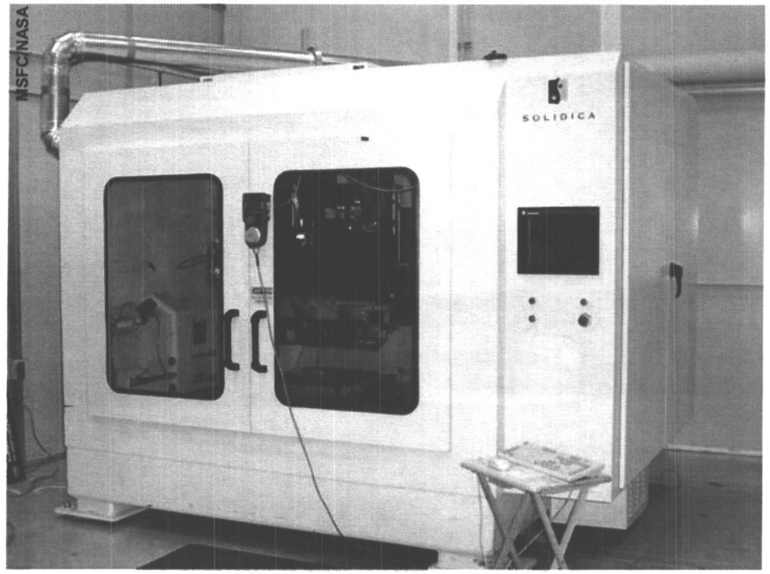


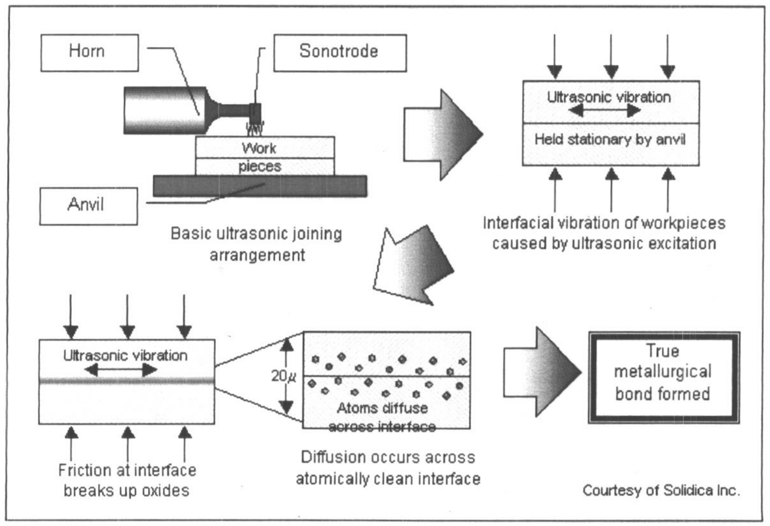
CNC Lathe System



Fabrication Technology Summary

Ultrasonic Consolidation (UC)

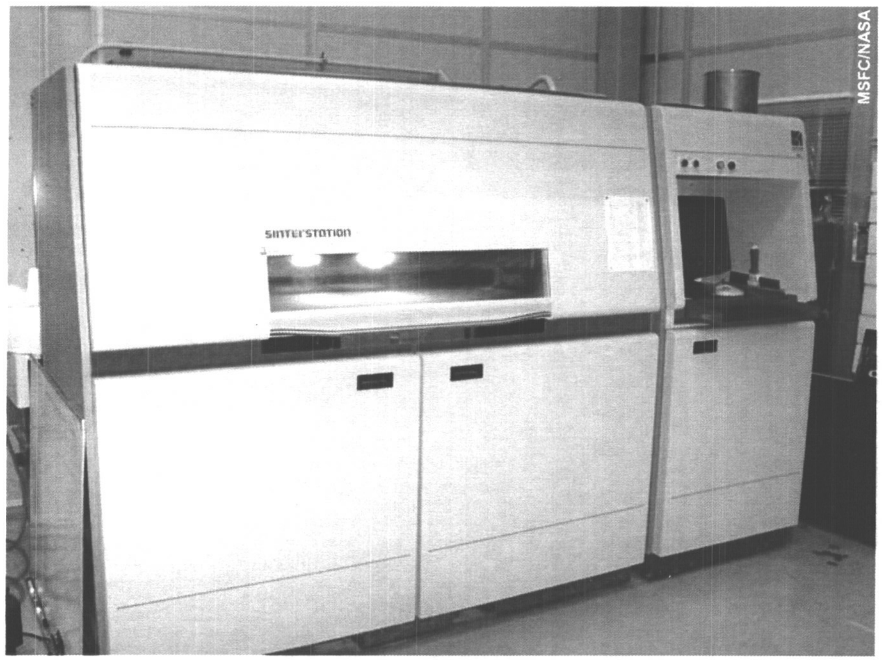




SSPO

Fabrication Technology Summary

Selective Laser Sintering/Melting (SLS/SLM)

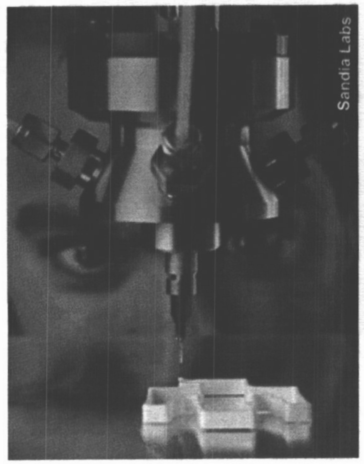


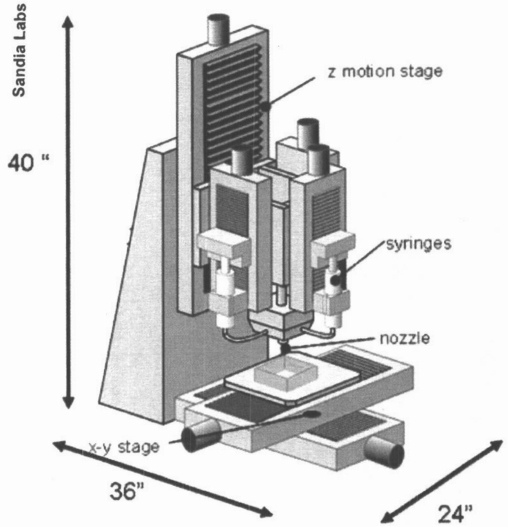
Fabrication Technology Summary

Fused Deposition Modeling (FDM)

Fabrication Technology Summary

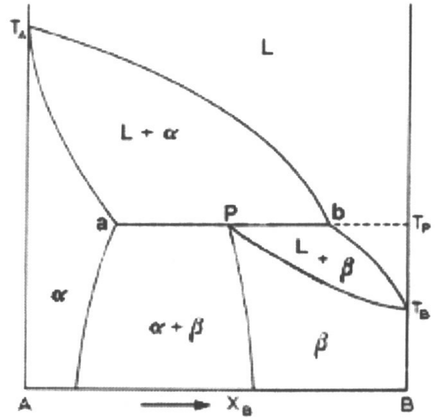
Robocasting





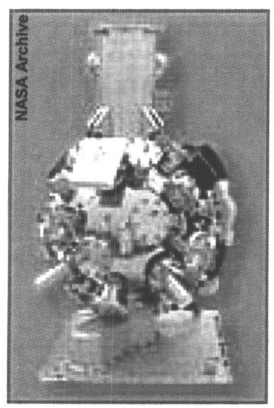
Fabrication Technology Summary

Casting Methods



Peritectic Alloys
(e.g. Amalgams)

Combustion
Synthesis
Experiments



SSPO

Fabrication Technology Summary

SSPO

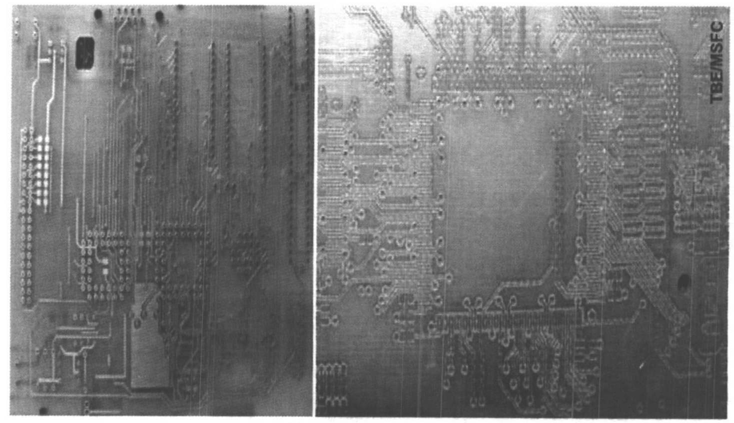
3D Printing

Trade Study Rankings For Electronics Fabricator

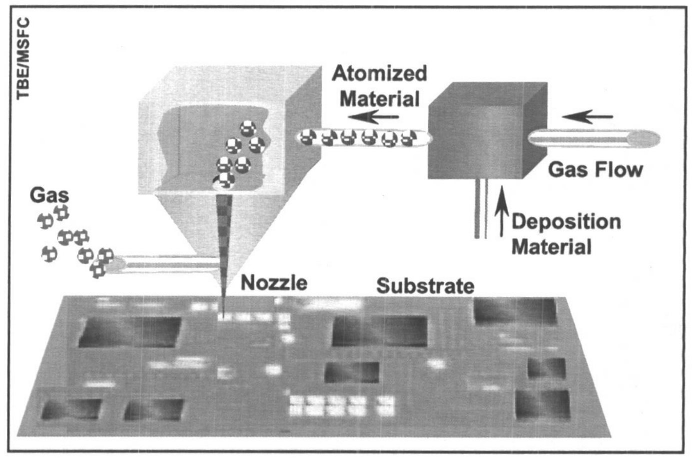
- Top Ranked Technologies Are Shown Below For Processing of Electronics

Technology
Electronics Parts Materials Milling (EPMM)
Electronic Parts Material Deposition (EPMD) (General class of 3D Printing methods)
Photolithographic Methods

- Recommend Separation of Electronics Fabrication As Separate Unit
  - Contamination Control Issues Are More Stringent Than MMF
  - Difference in Features Size of 2 to 3 Orders of Magnitude



Electronics Parts Materials Milling



Electronics Material Deposition

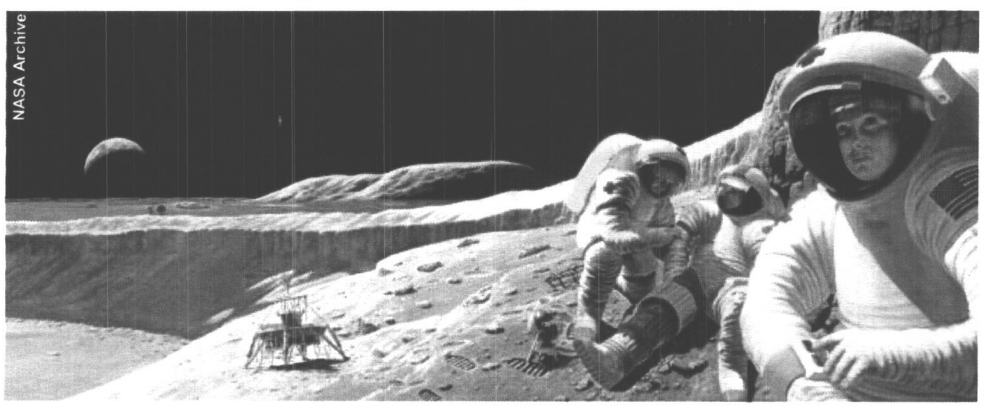
Trade Study - Recommendation For Electronics Fabricator

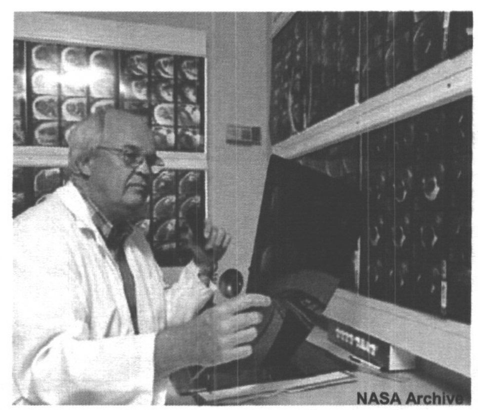
- Additional In-depth Study Recommended
  - This release focused on mechanical ability to create electronic features rather than electrical functionality testing
  - Maturity levels are at research levels for complex circuitry using 3DP methods, thus data was difficult to obtain
- Photolithography To Be Monitored for Emergence of New Processes
  - Emphasize elimination of photo-mask generation, exposure sources and component placement equipment requirements
  - Look for elimination of hazardous etchants and exposure chemicals
- Testing of Fabricated Circuitry is Recommended as Next Trade Study Phase
  - Examine range of feature sizes from interconnects to components
  - Examine range of component types (resistors, inductors, transistors, etc.)

SSPPO

Biological Fabricators - Medical Products

- Target treatment of major and minor injuries
  - Triage for return to Earth
  - Treatment on-site
- Medical Product examples
  - Invasive: pins, plates, stints, catheters, sutures, surgical tools and dental instruments, adhesives for tissue binding and affixing implants
  - Non-invasive: casts, orthodics, tubes, syringes, gloves
  - Dental: fillings, crowns, bridges, dental cement
- Additional capabilities required
  - Sterilization capability
  - Libraries for medical procedures, dental procedures, and medical product specifications



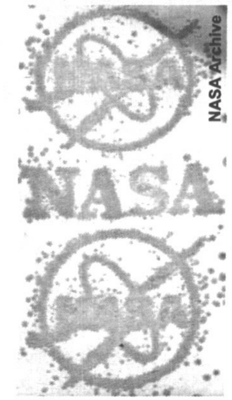


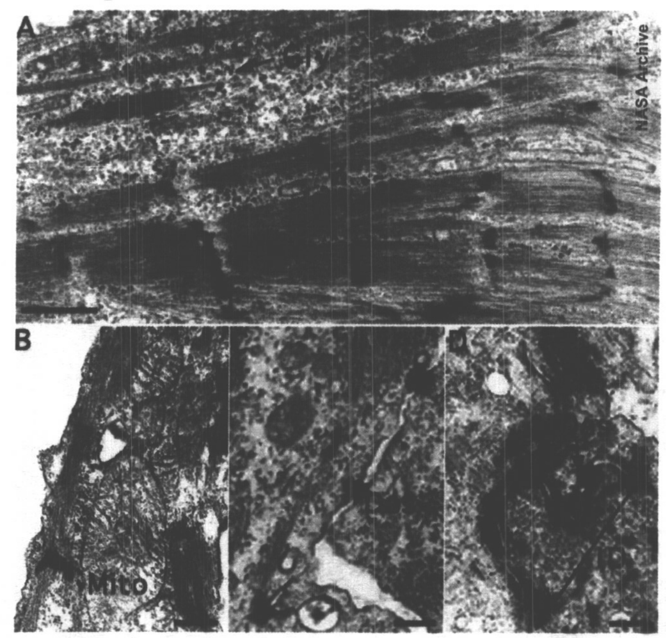
SSPO

Biological Fabricators - Bioplotter (Tissue Printing)

- Solid Freeform Fabrication (SSF)/Rapid Prototyping (RP) techniques for tissue printing
- Print viable human tissue on hydrogel scaffolds with high throughput, modified COTS inkjet printers
  - Aid in healing process
  - Replace damaged tissue
- Tissue Types
  - Near term capabilities - skin, bone, cartilage, connective tissue and blood vessels
  - Long range capabilities - other smooth muscle, skeletal muscle, and organs
- Potential development and demonstration of a Bioplotter for hypo-g and micro-g

Bioplotted E.coli Bacteria





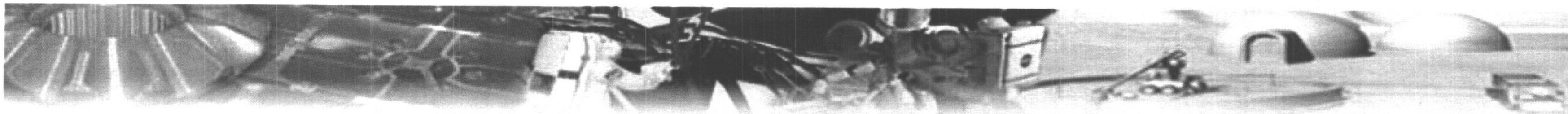
Micrograph of Printed Heart Tissue

SSPPO

Trade Study - Recommendation For Biological Fabricator

- Biological Fabricators have many promising applications being developed and will be monitored as part of this effort
- Further action in the near term has been deferred by MSFC

SSPO



Fabrication Systems Gaps

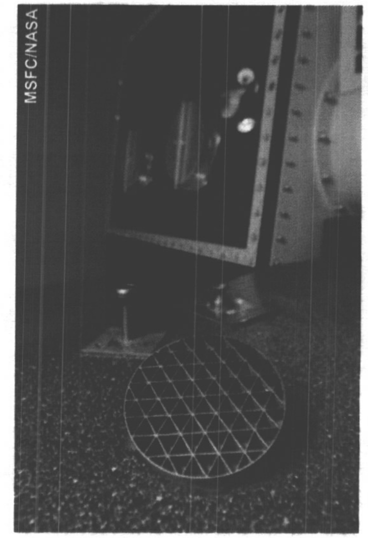
- STL Language for additive technologies is not adequate for precision part geometries
- In process NDE / Inspection for more accurate parts on additive fabricators
- Real time control feedback for modification of parameters as additive parts are being fabricated
- Additive Fabricators require secondary finishing by machining
- The most important of all:

<u>Lack of industry material standards for the output products of additive fabricators</u>

The effort to standardize the output of these machines for designers to utilize will be an intensive effort.

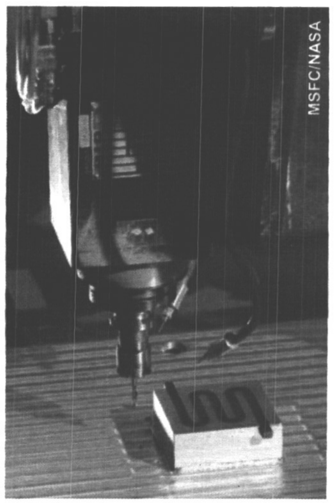
SSPO

Fabrication Technology Performance Validation Test Plan



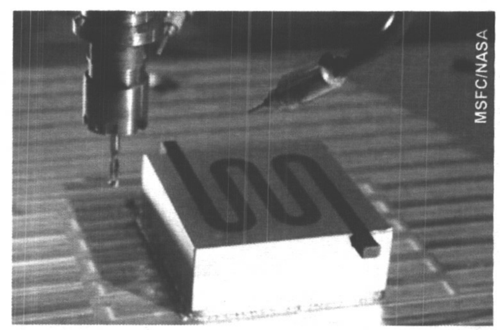
Purpose

- The test program will validate fabrication technology performance.



-- Limited information available outside of vendor-supplied data.

-- Supports Technology Development under Concept Formulation/Refinement

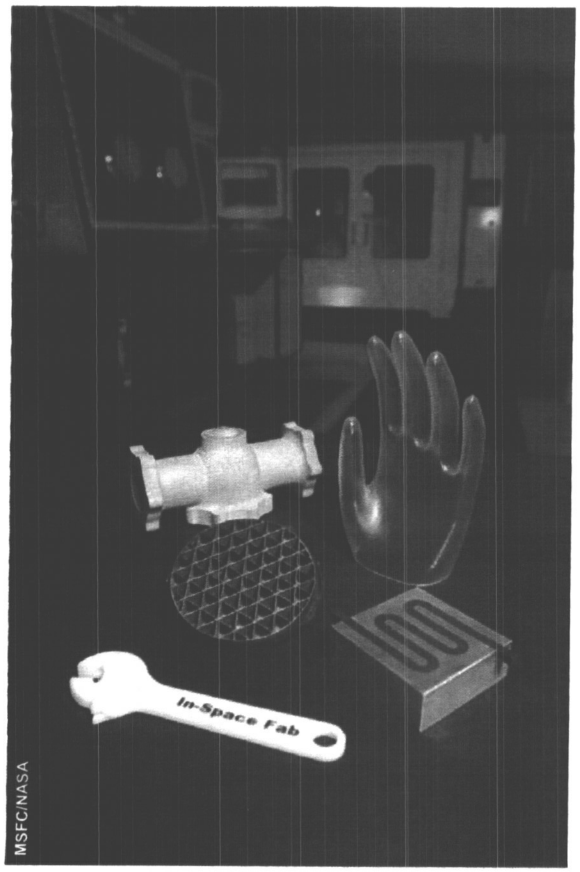


SSPO

Fabrication Technology Performance Validation Test Plan

<u>System Overview</u>

- Trade Study Assessed 30 Fabrication Processes



-- Distinct gap between "best" 9 technologies and remaining technologies.

-- Emphasis on the following technologies
  - Fused Deposition Modeling (FDM)
  - Selected Laser Sintering (SLS)
  - Ultrasonic Consolidation (UC)
  - Robocasting
  - Computer Numerical Control (CNC)

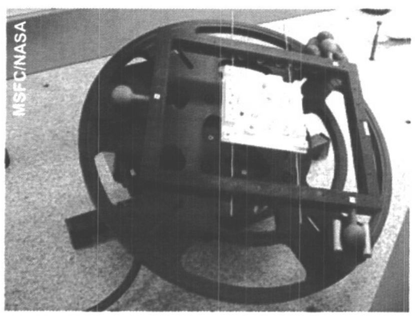
SSPO

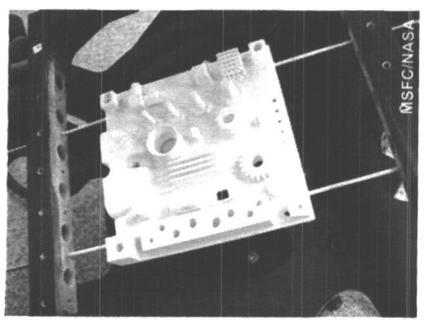
Fabrication Technology Performance Validation Test Plan

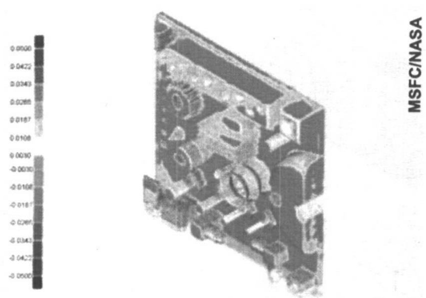
Test Methods

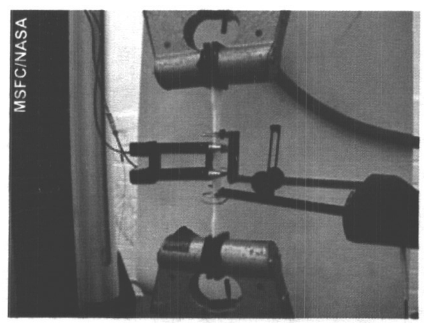
- The test program will assess dimensional accuracy, material properties, and ability to produce complex geometry.

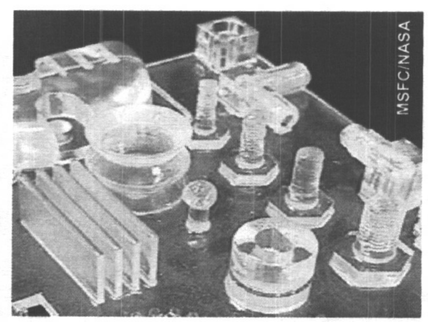
  -- Part accuracy determined by dimensional laser scanning.
  -- Tensile Pull Tests performed to validate Tensile Strength and % elongation.
  -- Benchmark part assessed to determine ability to produce complex geometry.







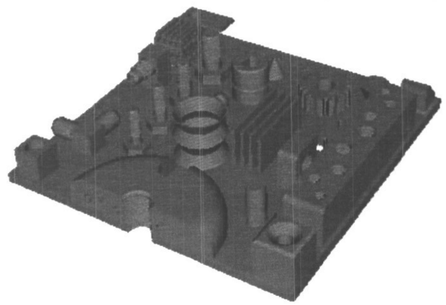




SSPO

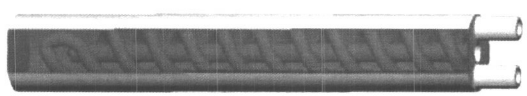
Fabrication Technology Performance Validation Test Plan

Test Parts: Dimensional Accuracy



- Benchmark Part: Determine dimensional accuracy of geometric features, and ability to build complex geometries.

- Simple Gear: Determine dimensional accuracy for component part.

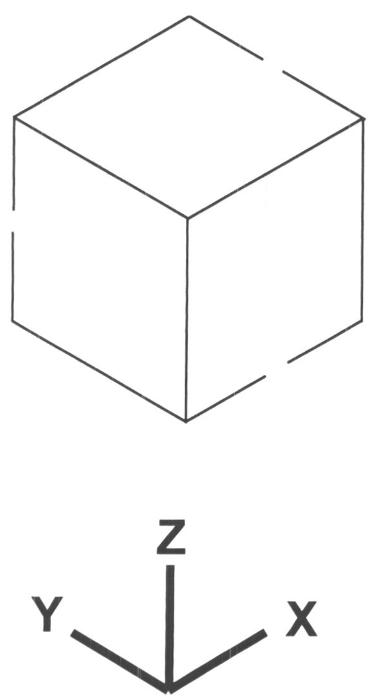


- Heat Exchanger: Determine ability to produce functional part with advanced features.

SSPO

Test Parts: Material Properties Assessment

- Tensile Test Specimens: Determine tensile strength of materials, including % elongation.



Part built in XY plane
Part built in Z plane

Fabrication Technology Performance Validation Test Plan

Ground Rules and Assumptions for Initial Testing

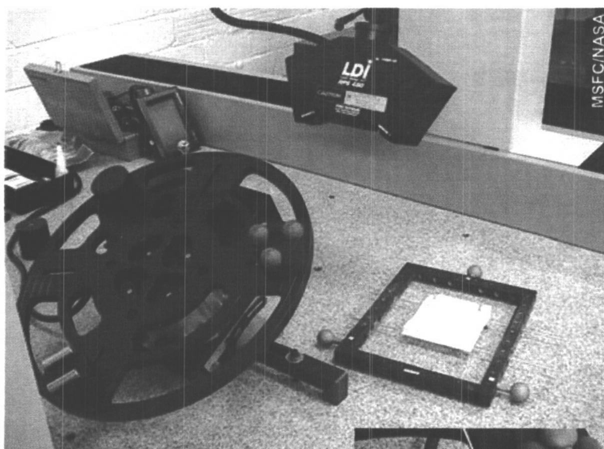
- Each process will fabricate parts using materials that are considered standard for the given process.
- Post-processing is limited to system-specific functions.
- Unconstrained test conditions
    - -- Environmental effects
    - -- Experience of technician
    - -- Time between part build and post-curing
    - -- Cleaning process variation

SSPO

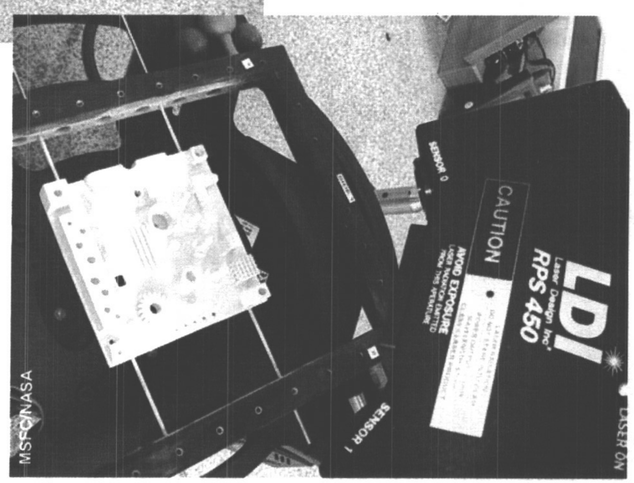
Fabrication Technology Performance Validation Test Plan

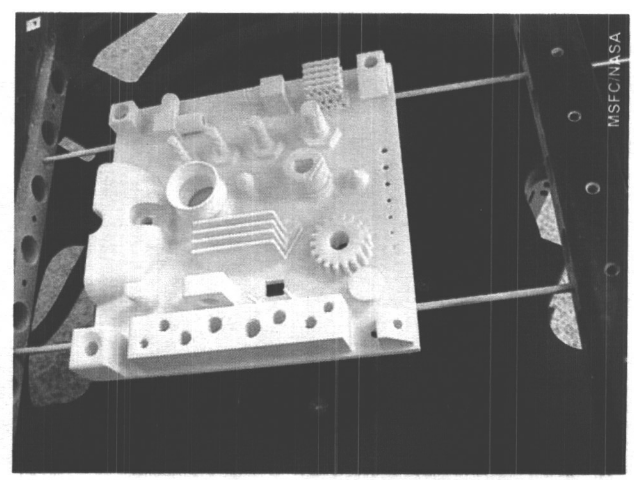
Test Specifications

- Dimensional Accuracy



-- No specification callout
-- Accuracy measured through the use of laser scanning technologies

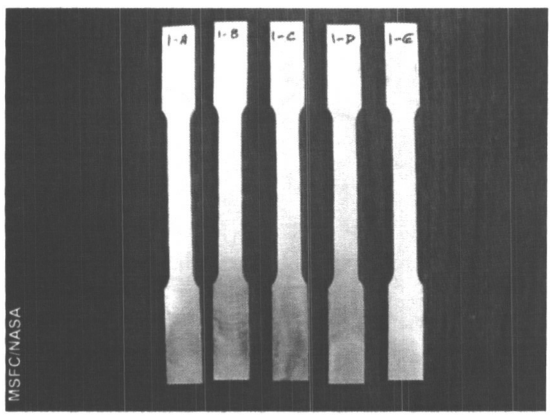


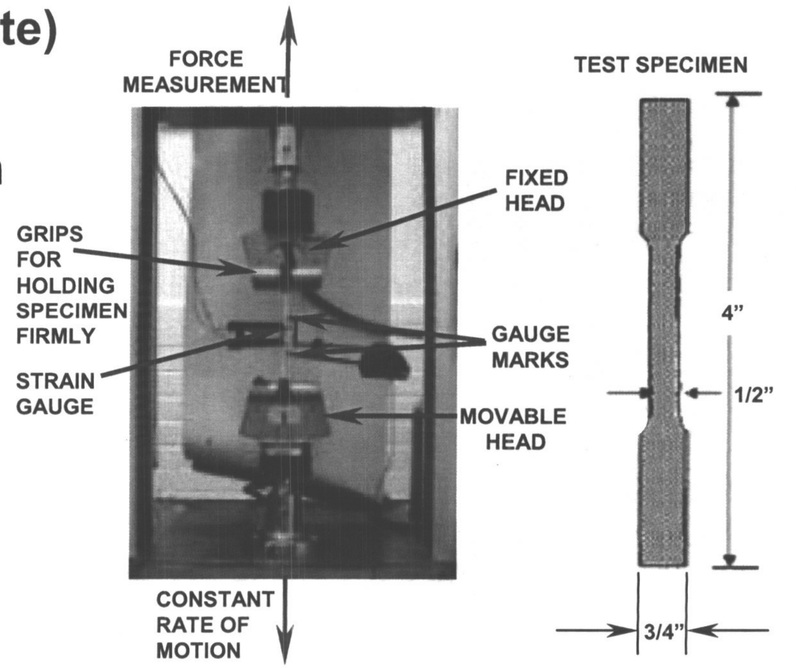


Fabrication Technology Performance Validation Test Plan

Test Specifications: Tensile Pull Tests

-- Plastic Parts per ASTM D638 (pull rate)
-- Test specimens per ASTM D638
-- Results will include Tensile Strength and % elongation





Tensile Tester and Specimen

-- Ceramic Parts per ISO 15490
-- Ceramic/Composite Parts per ISO 15733
-- Results will include Tensile Strength and % elongation

-- Metallic parts per ASTM E8 (pull rates)
-- Test specimens per ASTM E8
-- Results will include Tensile Strength and % elongation

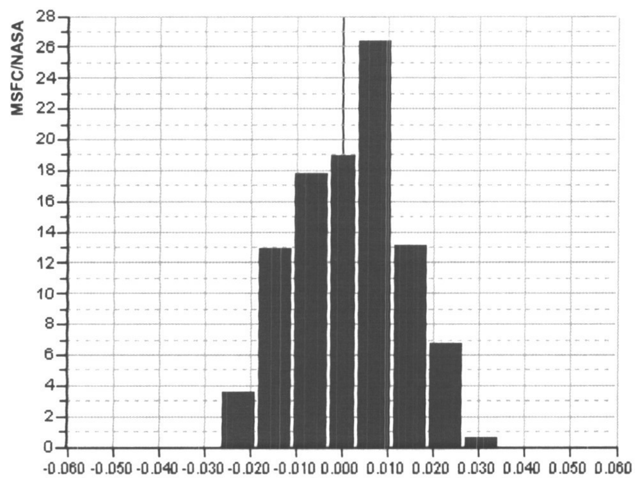
SSPO

Fabrication Technology Performance Validation Test Plan

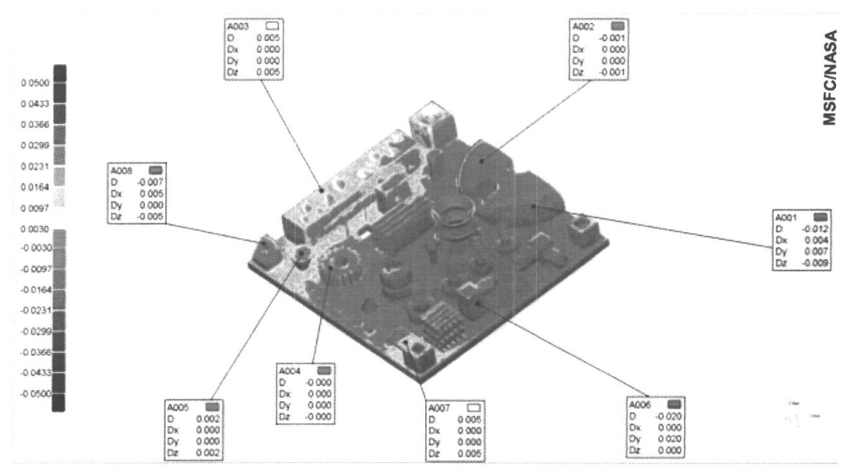
Results Analysis – Dimensional Accuracy

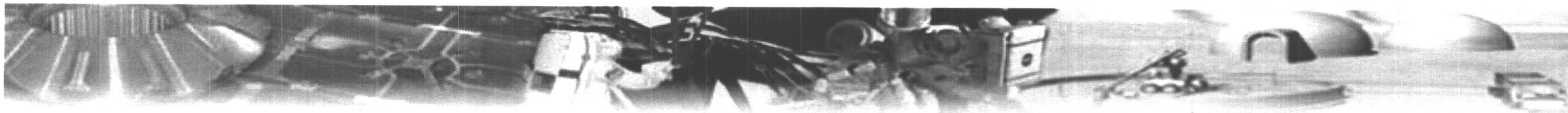
-- Laser scanner will provide results data
- Data collected from "visible" areas
- Can expect 1 million data points
- Data is electronically available

-- Post-processing will include detailed report
- Report provided for each scanned part
- Color plots showing deviations and locations



Deviation Distribution



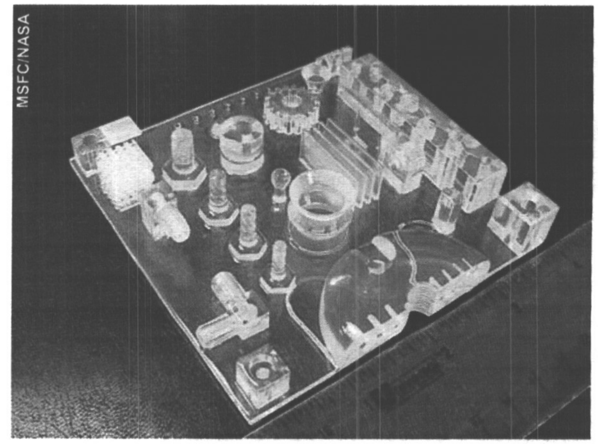


Fabrication Technology Performance Validation Test Plan

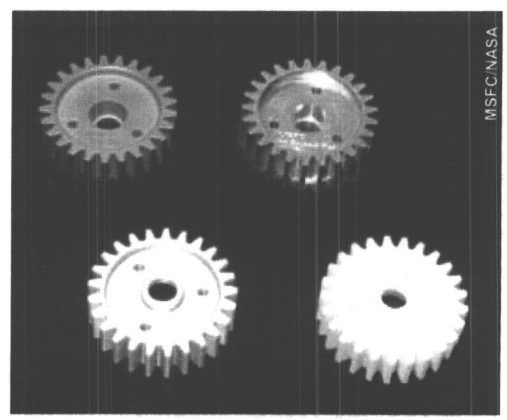
Results Analysis – Geometry Validation

Sample Results Table

Benchmark Features	Pass/Fail	Notes
Lattice Feature	Fail	Collapsed during build
Inverted cone	Pass	
Bellows	Pass	
Overall Accuracy	Fail	77% of inspection points have deviation > .005".

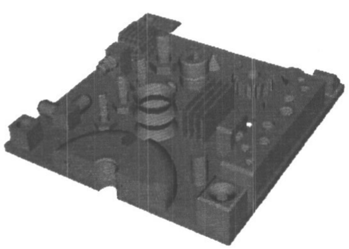


Benchmark features



Simple Gear

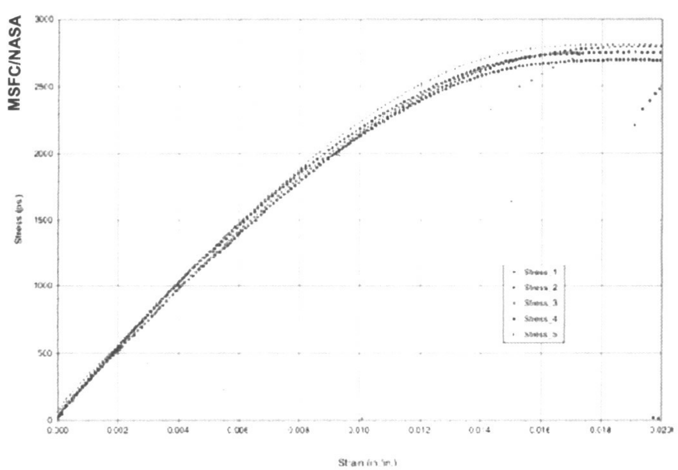
MSFC/NASA



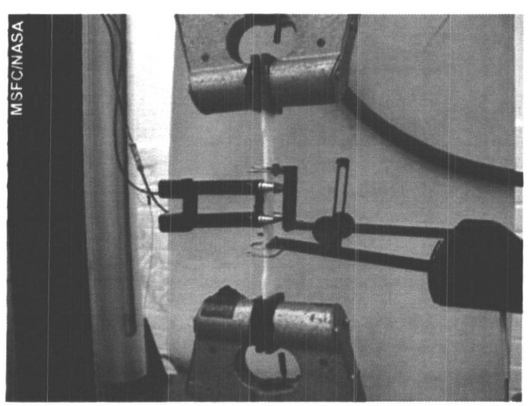
S S P O

Fabrication Technology Performance Validation Test Plan

Results Analysis – Tensile Pull Tests



- Measured material properties will be compared to vendor-supplied data.
- Material properties will be compared to MIL-HNBK-5 and MIL-HNBK-17 properties (transitioning to Metallic Materials Properties Development and Standardization (MMPDS) Handbook).



MSFC/NASA

Specimen: 1

[redacted]

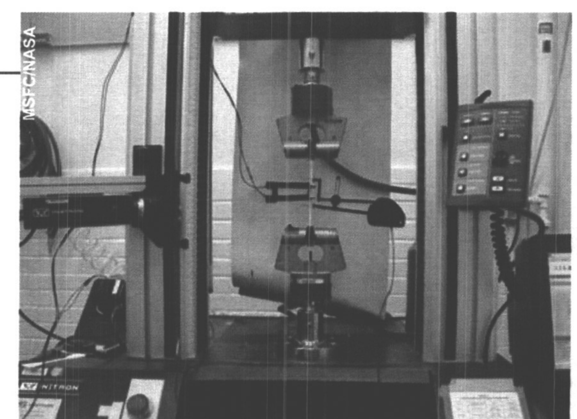
Width: 0.4980000 in
Thickness: 0.1015000 in
Ext. gauge len: 2.0000000 in
Spec gauge len: 2.5000000 in
Transverse Gauge Length: 0.50000 in

Specimen label: [F-X1-ABS]

Number of data points: 183

Maximum Load point: 159 — Maximum Load: 136.25337 lbf

Maximum Extension point: 173 — Maximum Extension: 0.04090 in



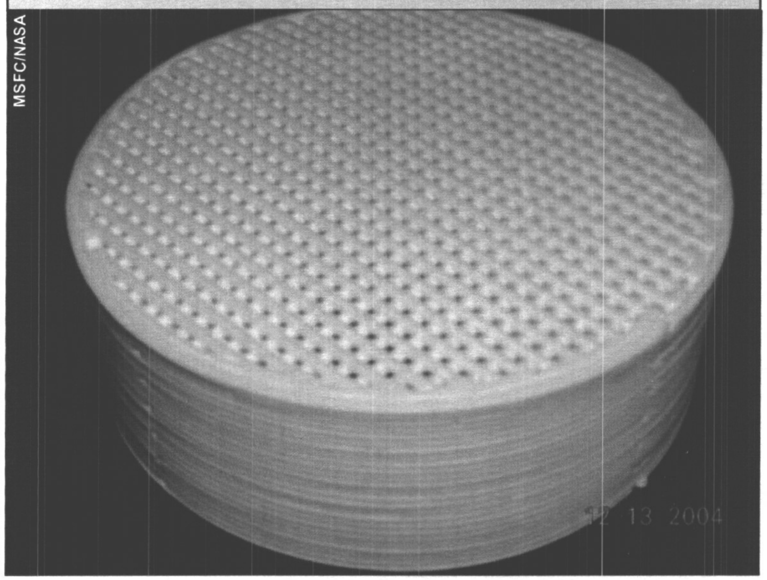
SSPPO

Fabrication Technology Performance Validation Test Plan

Current Validation Efforts

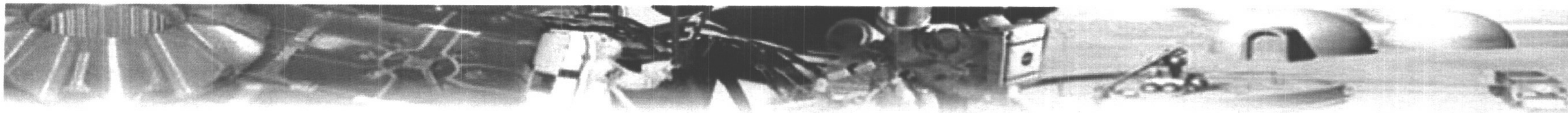
• Development of a ceramic (alumina) lattice structure used as a monolithic filter, impregnated with a catalyst.

ECLSS Catalyst Beds



• This structure may replace a catalyst bed of pelletized clay and zeolite.

SSPO



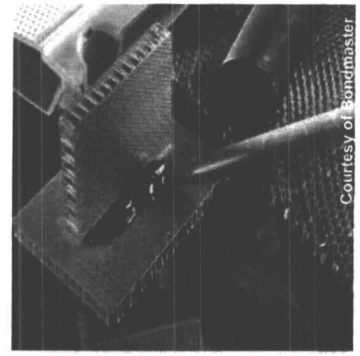
Lunar & Martian Repair and Nondestructive Evaluation (NDE) Development Overview

- Repair and NDE Selected Capabilities
- First Priority Capabilities Selection Rationale
- Multi-Material Joining, Patching and Filling
- Multi-Material Joining, Patching & Filling Tech Gaps
- Electrical Repair - Hand-held Tool
- Electrical Repair Hand-held Tool Technology Gaps
- NDE : QA & Safety Inspection and Troubleshooting
- NDE Recommendations
- NDE, QA, and Safety Inspection & Troubleshooting Technology Gaps

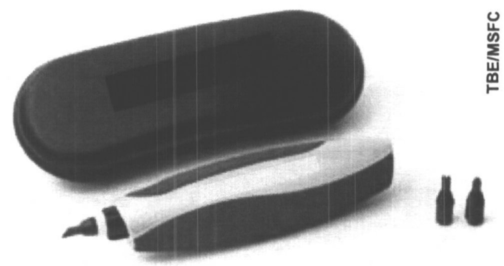
SSPO

Repair and NDE Selected Capabilities

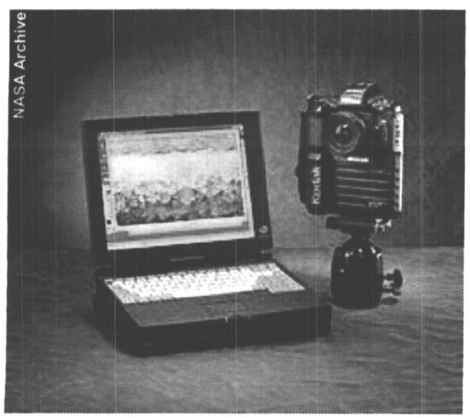
- Multi-Material Joining, Patching and Filling
  - Polymeric material adhesives and fillers
  - Metallic joining and fillers
    - Metals non structural
    - Metals structural

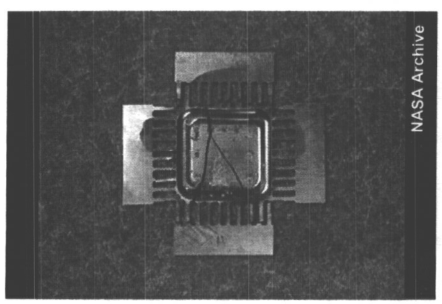


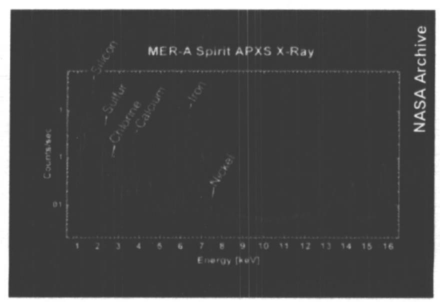
- Electrical repairs
  - Hand held tools
  - Repair station

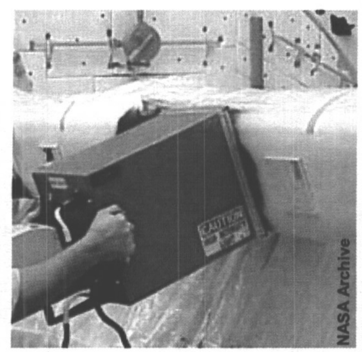


- Non Destructive Evaluation
  - Handheld diagnostic tools
  - Materials identification
  - Closed loop evaluation of fabricated parts
  - Repair process evaluation



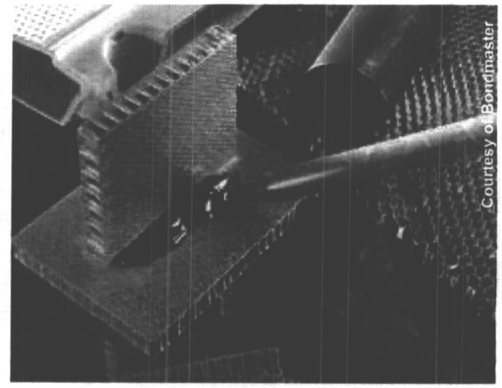




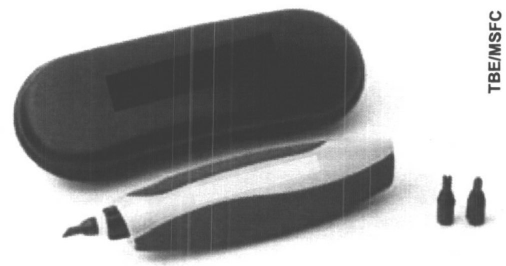


First Priority Capabilities Selection Rationale

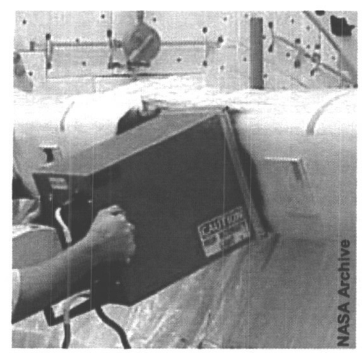
- Multi-material Joining, Patching and Filling
  - Responsiveness to safety and performance constraints
  - Responsiveness to materials selection by Exploration Systems Mission Directorate
  - Availability
  - Resource efficient
  - Ease of operations


Courtesy of Bondmaster

- Electrical Repair Handheld Tool
  - Alignment with failure analysis results
  - Flexibility to contingency failures
  - Minimal mass and volume solution
  - EVA operations


TBE/MSFC

- NDE QA & Safety Troubleshooting and Maintenance (Hand-Held/Portable)
  - Responsive to early spirals
  - Flexibility
  - Availability
  - Stepwise development of NDE capabilities suite

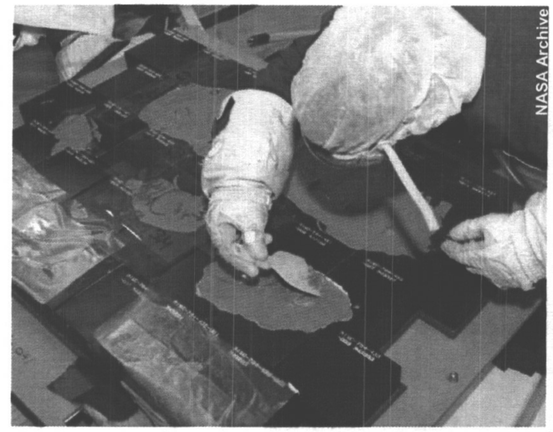

NASA Archive

SSPO

Multi-Material Joining, Patching and Filling

Capability Description:

- Adhesives, tapes, and amalgams-based repairs of similar materials; including:
  - Metals, plastics, composites, glass/ceramics
  - Single and multi-part systems
  - Manual and automatic mixing systems for two or multi-part components



Product Performance Characteristics

- General
  - 'Toolkit' of multiple bonding agents for pressurized cabin, and possible unpressurized special cases
- Materials
  - -Metals -50 to 300° F
  - -Plastics -20 to 200° F
  - -Glass/Ceramics -25 to 2,500° F service temperatures
- Shelf Life 6 months minimum

SSPO

Multi-Material Joining, Patching & Filling Tech Gaps

- Identification of adhesive and amalgam materials
  - Compatible with CEV, habitat, robotic equipment, rovers (currently yet to be determined, although will anticipate materials selections commensurate with good aviation/aerospace practices).
- Bonding agent volatility
  - Manned environment off/out gassing during applications
- Storage temperatures and Shelf Life
  - Frequently, typical temperatures advantageous to assuring storage longevity involve some amount of moderate control, including refrigeration at 0 to 40°F, to cases of compatibility with room temperature.
- Longevity of repair
  - Radiation, such as UV, environmental moisture, and external environmental temperature exposure effects may also be significant in inducing deleterious results to the adhesive material strength and life expectancy.
- Qualification
  - Satisfactory and representative flight adhesive repair techniques via appropriate development and preflight verification plan efforts.
- Unknown Environmental effects
  - Microgravity, low-g, and other pressurized/depressurized environmental material behavior - Adhesive/amalgam application/distribution methods

    - Curing requirements - Viscosity requirements - Material strength modification/derating by void content, porosity, and other factors.

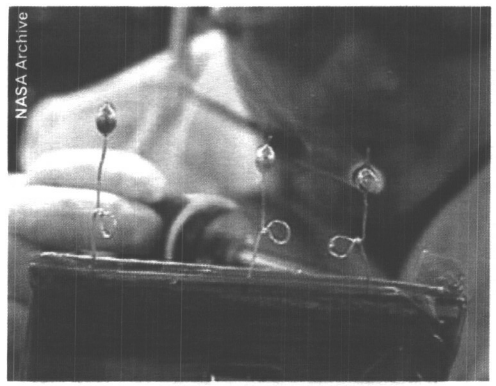
SSPO

Electrical Repair - Hand-held Tool

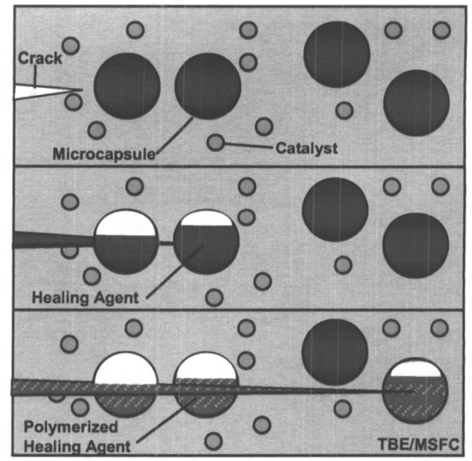
Capability Description:

•Ability to make temporary and permanent repairs, using a handheld self-contained repair tool, on electronic equipment printed wiring boards and electrical wiring connections during IVA or EVA

- Solder Joint Repair
- Wiring Repair



ISS Soldering Demo



Self-Healing Wire Insulation Diagram

Product Performance Characteristics:

• Materials	Basic solder families for electronic equipment compatible with flight hardware
• Compatibility	Repair is 100% compatible with base material
• Electrical	Functional per baseline design
• Operating Life	MTBF per baseline design
• Process Availability	Crew utilization from tool suite

SSPO

Electrical Repair Hand-held Tool Technology Gaps

- Functionality and performance in in-space environments: Vacuum, temperature and microgravity effects are untested

- An ergonomic design of the flight hand-held soldering tool is required; current study based on commercial versions of the tool

- Space-qualified electrical repair tool design; current study based on commercial versions of the tool

- Shelf life under operating environments; the effects of space environments on the stability of the material are untested

- Tool and materials compatible with EVA suit; repair tool and repair materials may damage EVA suit.

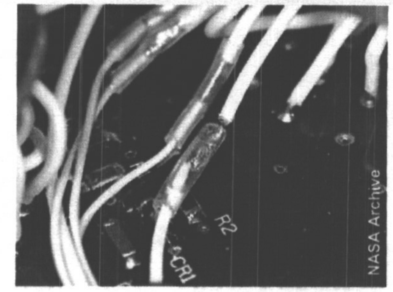
- Safety issues associated with molten materials; need to encapsulate or enclose molten solder.

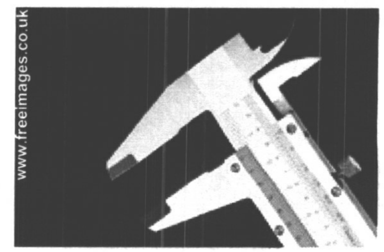
- Higher wattage tool needed; to meet repair requirement (approximately 100 W), and possible variable power settings

NDE : QA & Safety Inspection and Troubleshooting

Capability Description:

- Hand-held NDE equipment for routine inspection of critical components
- Hand-held NDE for QA of adhesive bonding
- Hand-held NDE to check wire insulation for cracks and breakages
- Multi-meter for electronic component test and checkout





Product Performance Characteristics:

• Materials	Inspection of wire insulation, metals, composites, ceramics, plastics, habitat materials (concrete, etc.)
• Size of Hardware	Handled and operated by a single crewperson
• Telemetry	Data capable of downlink to ground for analysis
• Defect Detection	Equivalent to current techniques used in the aerospace industry
• Process Availability	Crew utilization from tool suite

SSPO

NDE Recommendations

- Crack and flaw detection technologies (12 methods evaluated)
  - Thermographic and Laser Ultrasonic selected
    - Laser Ultrasonics is focus of development
    - Thermographic cameras are "commercially ready" with little enhancement required

- Imaging technologies (9 methods evaluated)
  - Digital Radiography and Micro Millimeter Wave selected
    - Downsizing for hand-held/portable
    - Good potential for future capability applications
    - Evaluation of volumetric hardware.

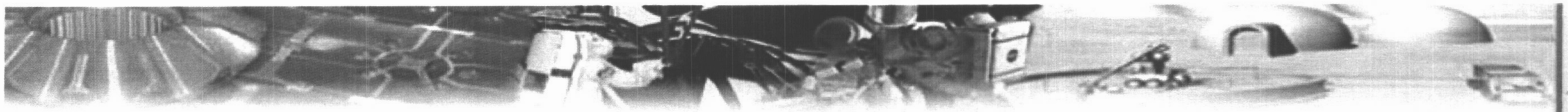
- Electrical Test and Checkout
  - Multi-meter electronic testers are well advanced for basic electronic equipment checkout
  - Oscilloscopes, power supplies, and other 'standard' test instruments

NDE, QA, and Safety Inspection & Troubleshooting

Technology Gaps

Gap Description	Application to Technology
Functionality and performance in space environments is not well established	Laser ultrasonic, microwave-millimeter wave, thermography, digital radiography
Size of equipment is not compatible with hand held operation	Laser ultrasonic
	Microwave-millimeter wave
Shelf life under operating environments	All technologies
Imaging technologies are currently functional for surface evaluation only or penetrate only nonmetallics	Microwave-millimeter wave
	Thermography
Known reference standards required	Thermography, laser ultrasonics, digital radiography, Microwave-millimeter wave
Coatings may affect results	Thermography
Robotic NDE capability	All technologies

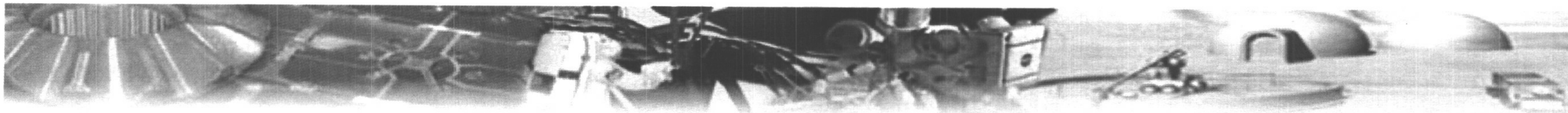
SSPO



Lunar & Martian Habitat Structures Development Overview

- Habitat Structures – Introduction
- Habitat Structures – Interfaces
- Habitat Structures – Construction Products
- Habitat Structures – Sub-element Interfaces
- Habitat Structures - Raw Regolith
- Habitat Structures - Block Structures
- Habitat Structures - Reinforced Concrete
- Habitat Structures - Deployable Metal Structures
- Habitat Structures - Thin Films/Inflatables
- Habitat Structures - Glass Products
- Habitat Structures – Fabrication Challenges
- Habitat Structures - Near-Term Development Activities
- Habitat Structures - Potential Tests Requiring Cryogenics Test Bed

SSPO



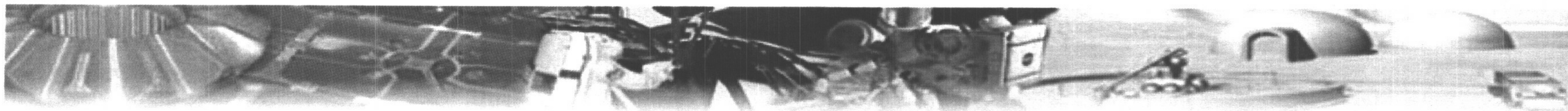
Habitat Structures - Introduction

- ***Habitat* Structures Purpose:**
  - Develop Lunar and/or Martian habitat structures for manned missions that maximize the use of in situ resources to address the following agency topics:
    - Bioastronautics Roadmap (BR) risks
      - Risks 31-35 (Radiation Health) & 43-44 (ALS)
    - Strategic Technical Challenges defined in Human & Robotics Technology Formulation Plan, v. 3.0
      - Margins & Redundancy
      - Modularity
      - Robotic Networks
      - Affordable Logistics Pre-positioning
      - Reusability
      - Autonomy
      - Space Resource Utilization

SSPPO

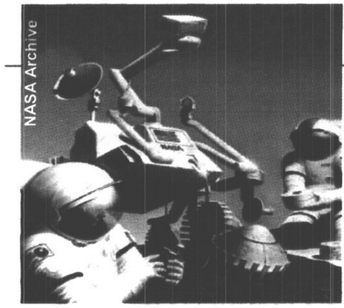
Habitat Structures - Introduction

- ***Habitat Structures - Requirements***
  - **Support a pressurized (shirtsleeve) environment for the crew**
  - **Protect the crew from a worst case radiation (GCR & SPE) exposure**
  - **Protect the crew from micrometeorites and exhaust plumes**
  - **Initially, be able to be fabricated in advance of a manned crew so as to provide immediate protection (semi-autonomous construction)**
  - **Early, achievable, and visible milestones and successes are required**
  - **Development should be evolutionary and scalable**
  - **Present a psychologically/ergonomically compatible living environment for the crew**



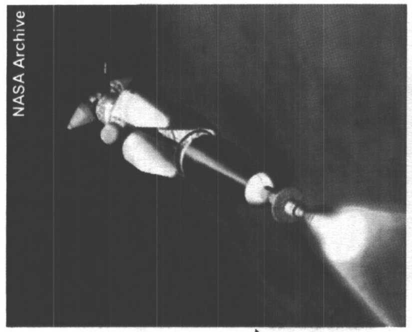
Habitat Structures - Interfaces

Crew



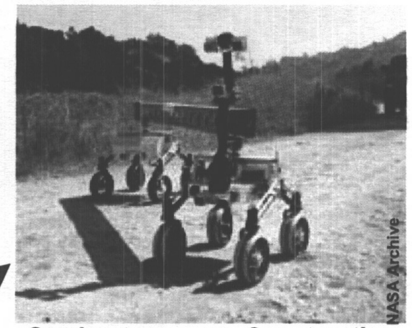
- Radiation Shielding
- Shelter and Storage
- Hermetic Atmospheric Environment
- Assembly, maintenance and repair support
- Micro-meteorite hit protection
- Exhaust Plume protection

Vehicle



- Transportation of equipment up-mass / up-volume
- Temporary Shelter
- In-flight habitat materials development

Robotic

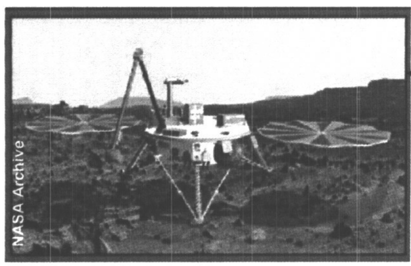


- Semi-autonomous Construction
- Scouting: exploration of resources
- Materials Sampling
- Information Gathering: locations,
- scheduling, prioritization

ISFR

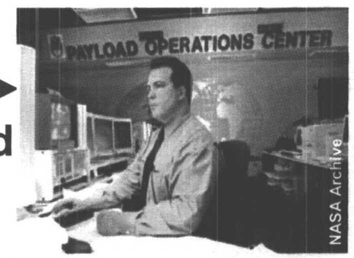
- Fabrication
- Repair
- NDE/NDI/NDT
- Recycling
- Habitat Structures

ISRU



- Feedstock for fabrication and repair materials
- Regolith by-products (glass, metals, thin films, etc.)

Ground Ops

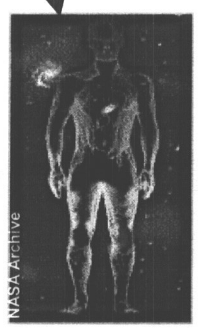


- Operations Management & Decision Support
- Exploration Planning
- In-Situ feedback analysis

Spiral 5 Applications

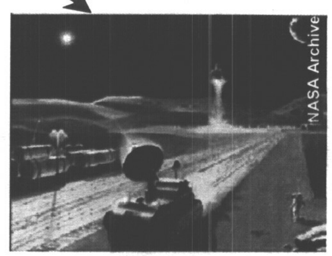
- Technology Development for Spiral 5 Applications
- Technology Maturation/Extension

ECLSS



- ALS
- EVA
- Power
- Cooling
- Heating

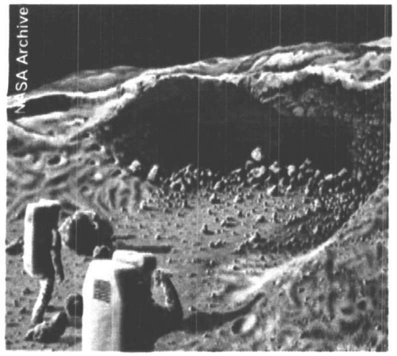
Logistics



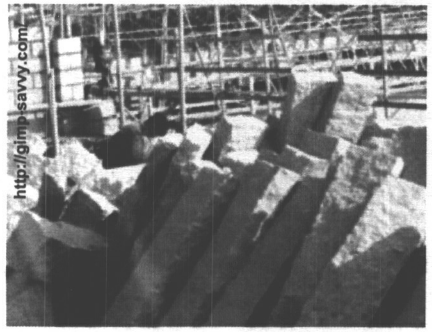
- Provisions
- Parts and Supplies

SSPO

Habitat Structures – Construction Products

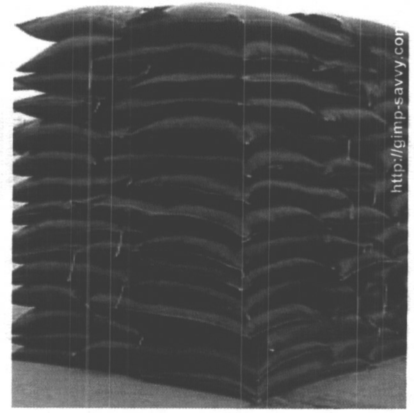


Raw Regolith

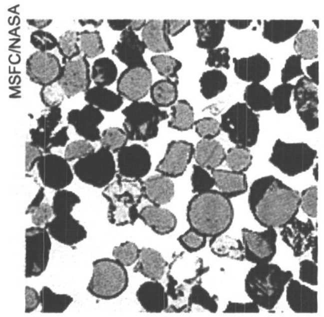


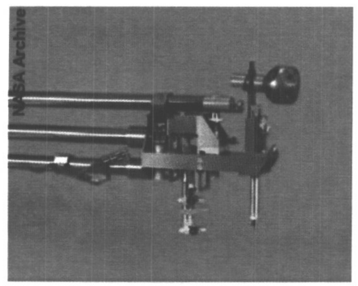
Blocks

Sand Bags

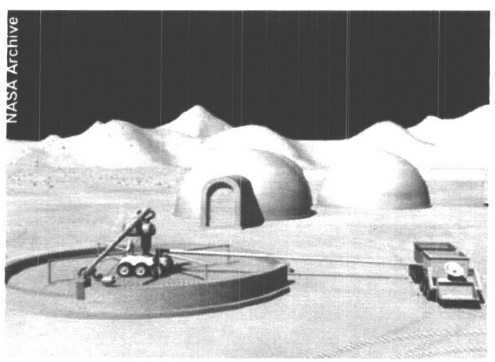


Glass Products



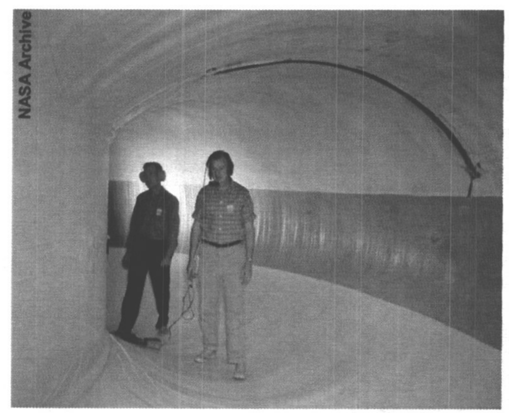


Deployable Metal Structures



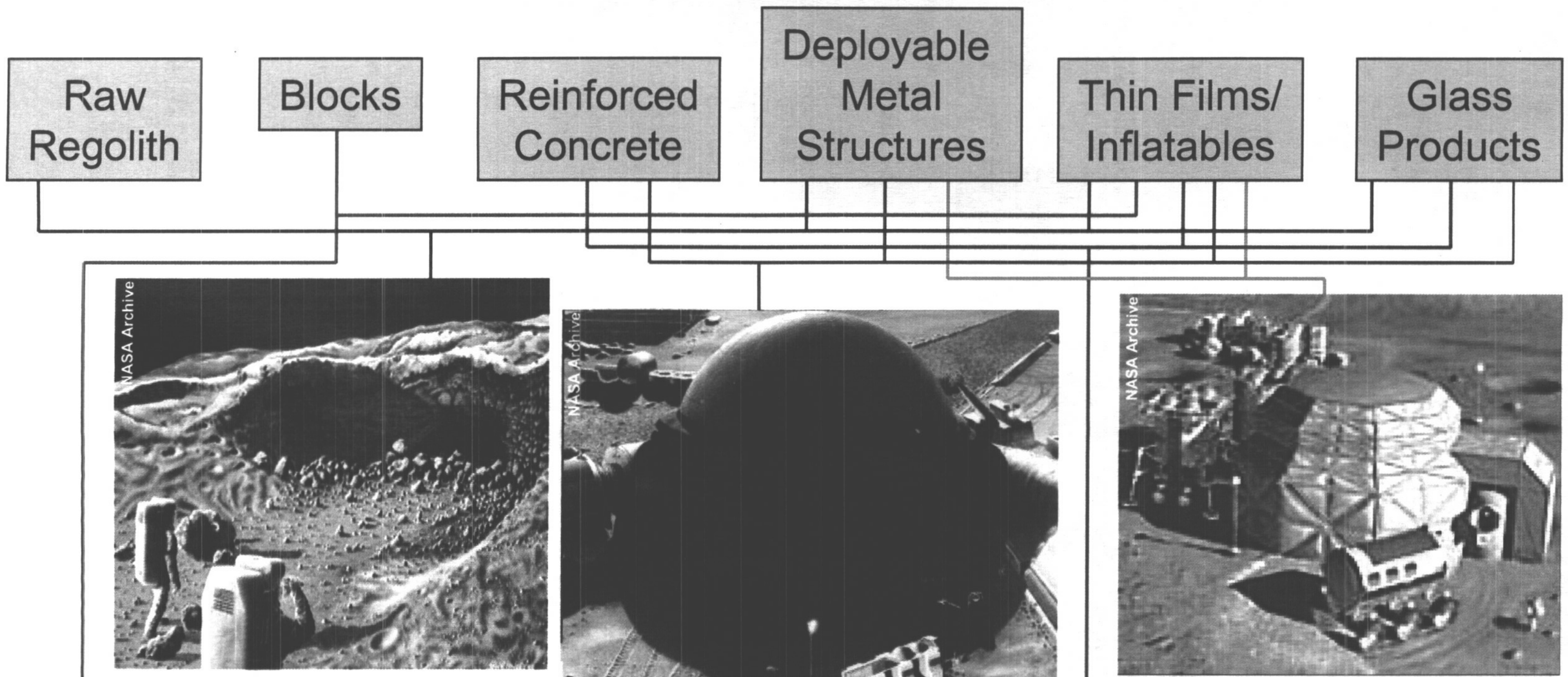
Reinforced Concrete

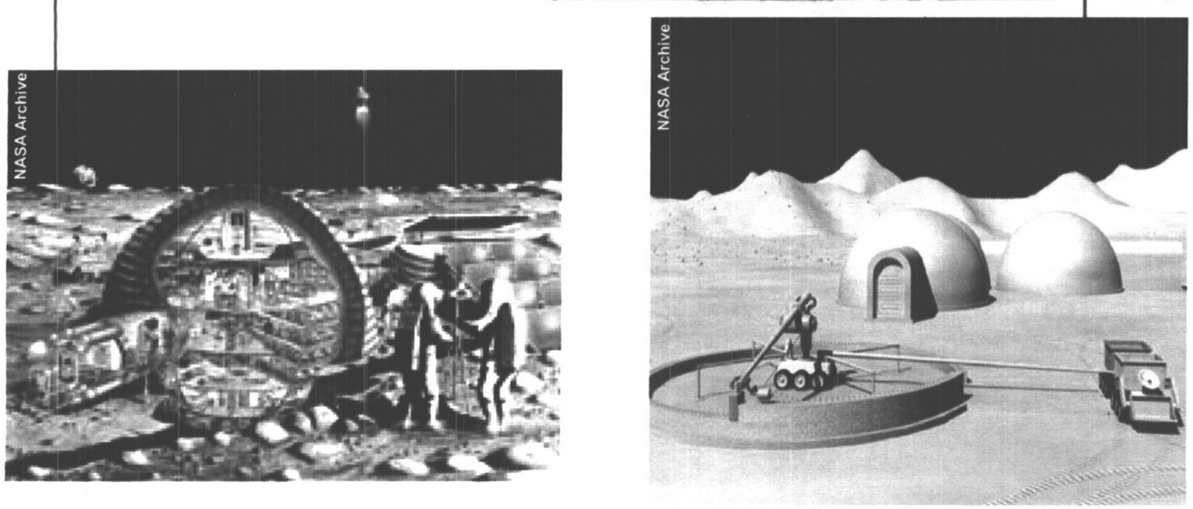
Thin Films / Inflatables



SSPO

Habitat Structures – Sub-element Interfaces

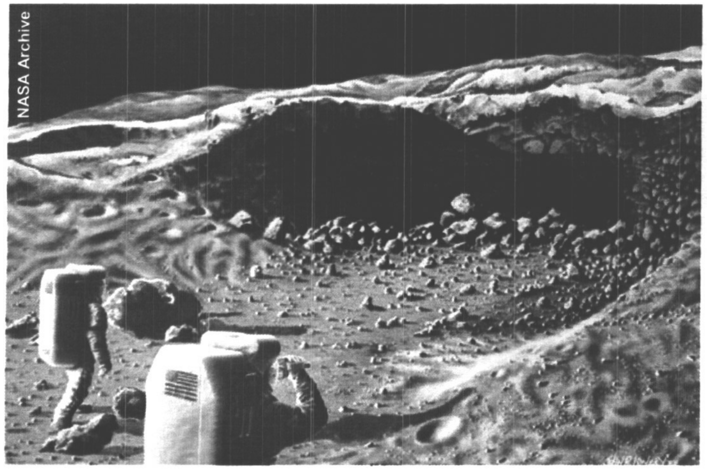




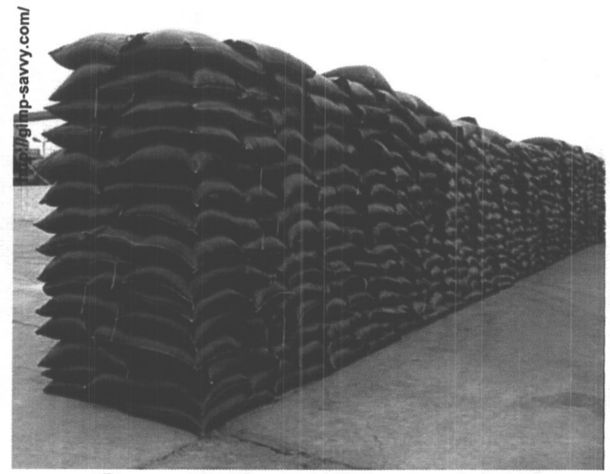
Various combinations of construction elements lead to significantly different habitat structure configurations – trade studies and characterization of materials are the key!

SSPO

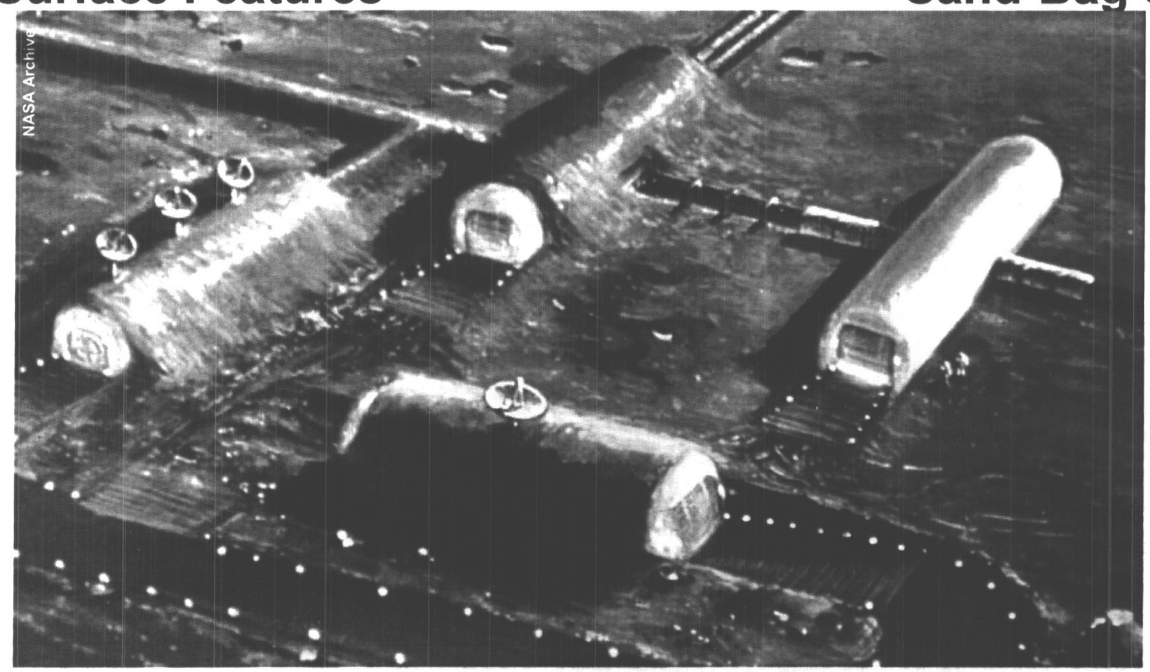
Habitat Structures - Raw Regolith



Sub-Surface Features



Sand-Bag Structures

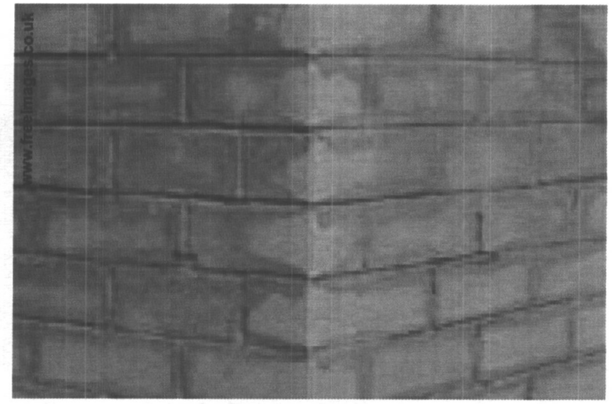


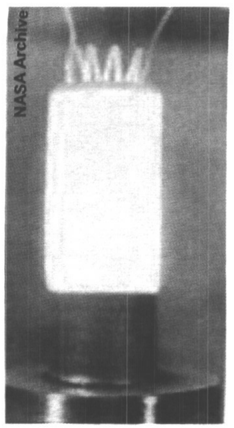
Buried Structures

SSPO

Habitat Structures - Block Structures

Compacted
Regolith Blocks





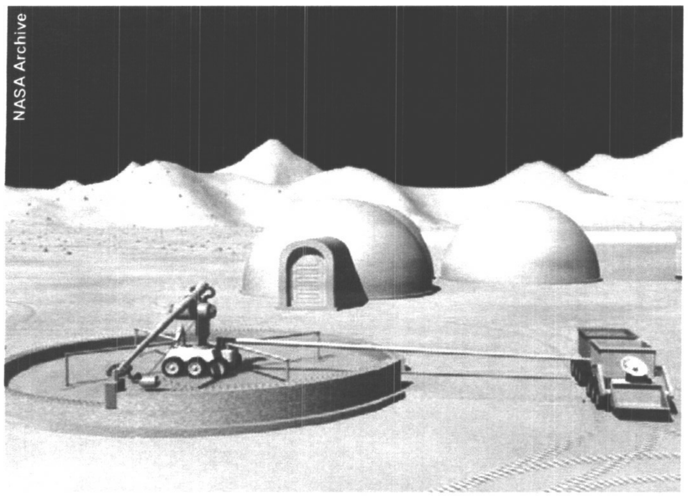
Sintered Blocks

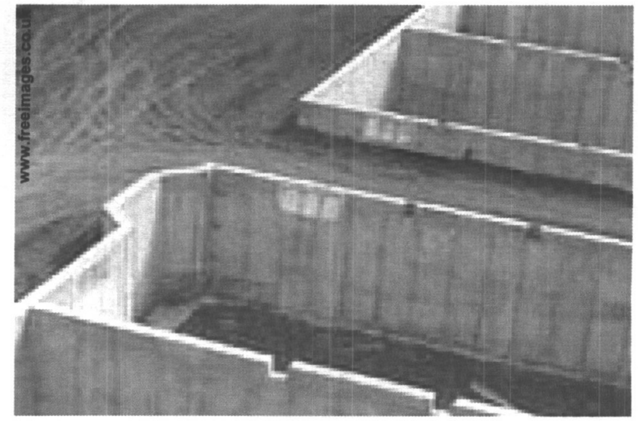
Carved Rock

SSPO

Habitat Structures - Reinforced Concrete

Lunar Contour Crafting (LCC)





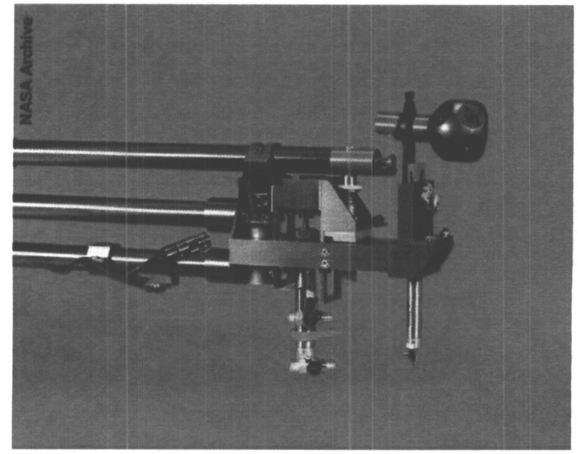
Pre-Cast, Pre-Stressed Panels

Inflatable Concrete Structures

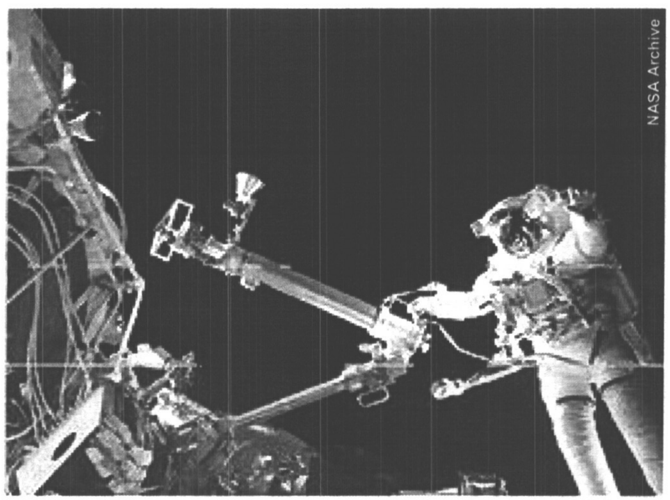
SSPO

Habitat Structures - Deployable Metal Structures

Foldable Metal Structures



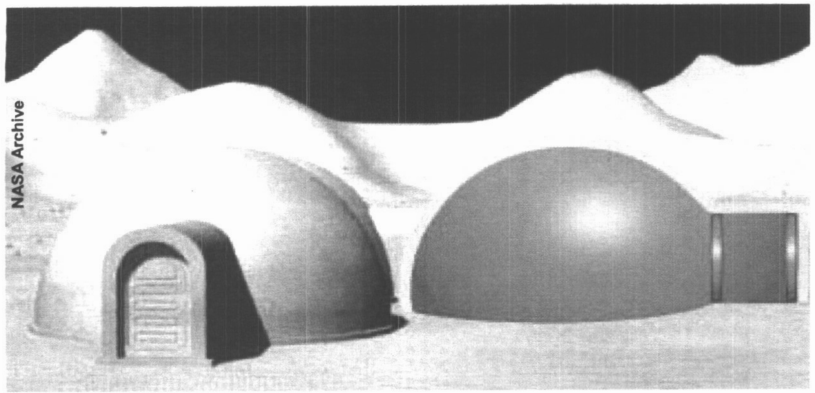
Expandable Structures



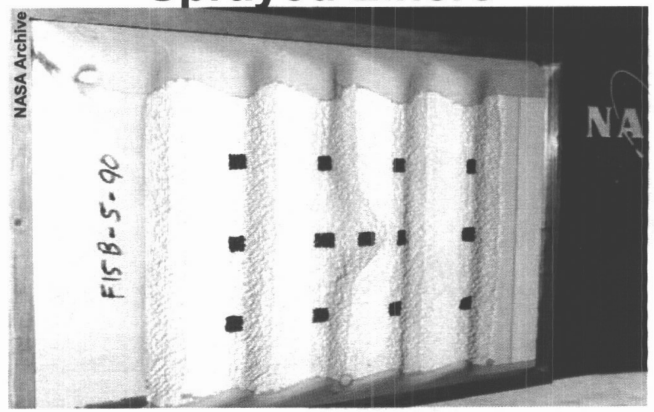
SSPO

Habitat Structures - Thin Films/Inflatables

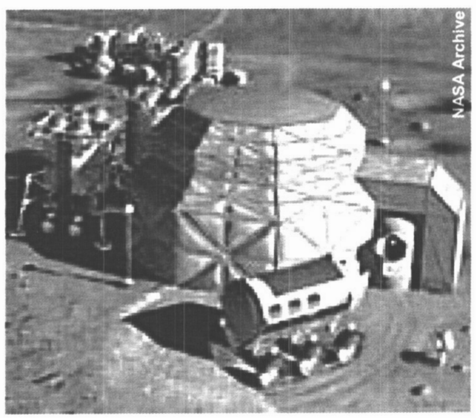
Nested Inflatables



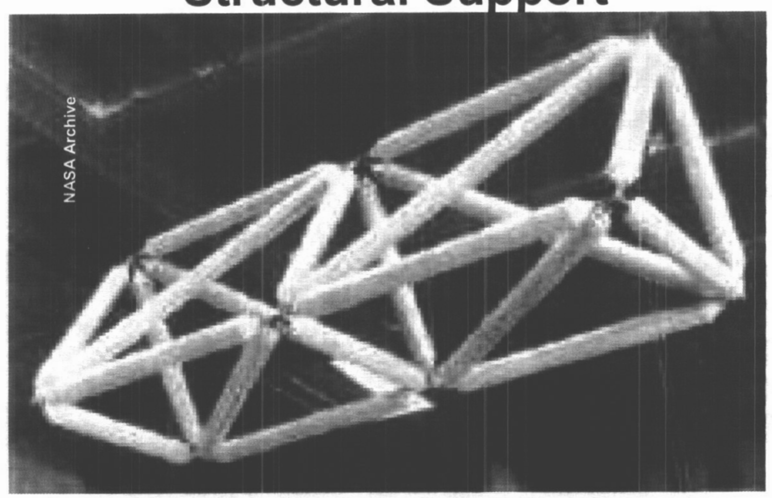
Sprayed Liners



Stand-Alone Inflatables



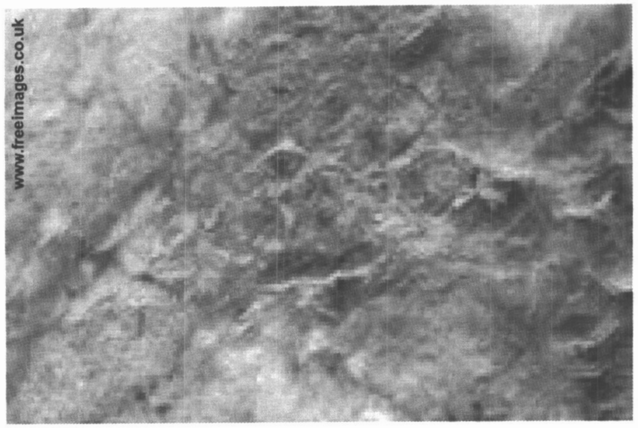
Structural Support



SSPO

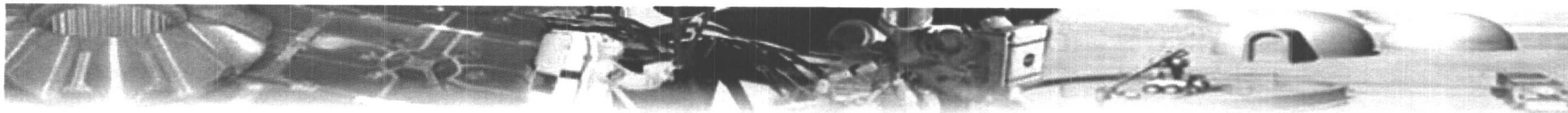
Habitat Structures - Glass Products

Fibers/Rods



Plate

SSPPO



Habitat Structures – Fabrication Challenges

- Lunar soil (regolith) is well characterized, but from limited locations (Apollo, Luna, Surveyor)
- Probable South Pole location of Moon base is essentially uncharacterized
- Lack of large quantities of high quality Lunar Regolith Simulant (LRS)
- Design must support high tensile loads due to pressurized environment – habitat is a pressure vessel!
- Unique environment requires unique test equipment/facilities
- Pre-manned mission construction requires complex robotics and teleoperations
- Integration of utilities and radiation shielding materials
- Configuration-specific technical challenges, for example:
  - Reinforced Concrete
    - Extruded in place vs. pre-cast, pre-stressed
    - Steel vs. glass rod reinforcement
    - Water-based vs. waterless concrete
    - Hermeticity

SSPO

Habitat Structures - Near-Term Development Activities

- Lunar regolith simulant characterization
  - JSC-1 (NASA/JSC)
  - JPT-1890 (Jensan Scientific)
- Concrete development/testing
  - Sulfur & LRS-based concrete testing in work
    - Significant improvements in tensile & compressive strength over Portland cement-based concrete
  - Effects of simulant on materials properties to be evaluated
  - Testing with prototype Contour Crafting system at MSFC
- Compacted block development/testing
  - Binderless compacted JSC-1 LRS block did not hold together
  - Evaluating potential binders
- Radiation shielding modeling/testing of candidate configurations
- Evaluation of all technologies with respect to acceptance criteria (being defined), including TRL and RD^3 assessment
- Definition of technology exit criteria

SSPO

Habitat Structures - Potential Tests Requiring Cryogenics Test Bed

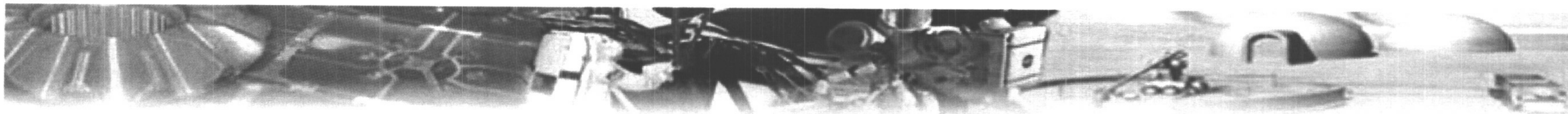
- Mechanical properties of block and concrete formulations as a function of temperature (-125 - +125°C)
  - Tensile
  - Compressive
  - Flexural

- Thermal properties of block and concrete formulations as a function of temperature
  - Thermal expansion
  - Thermal conductivity

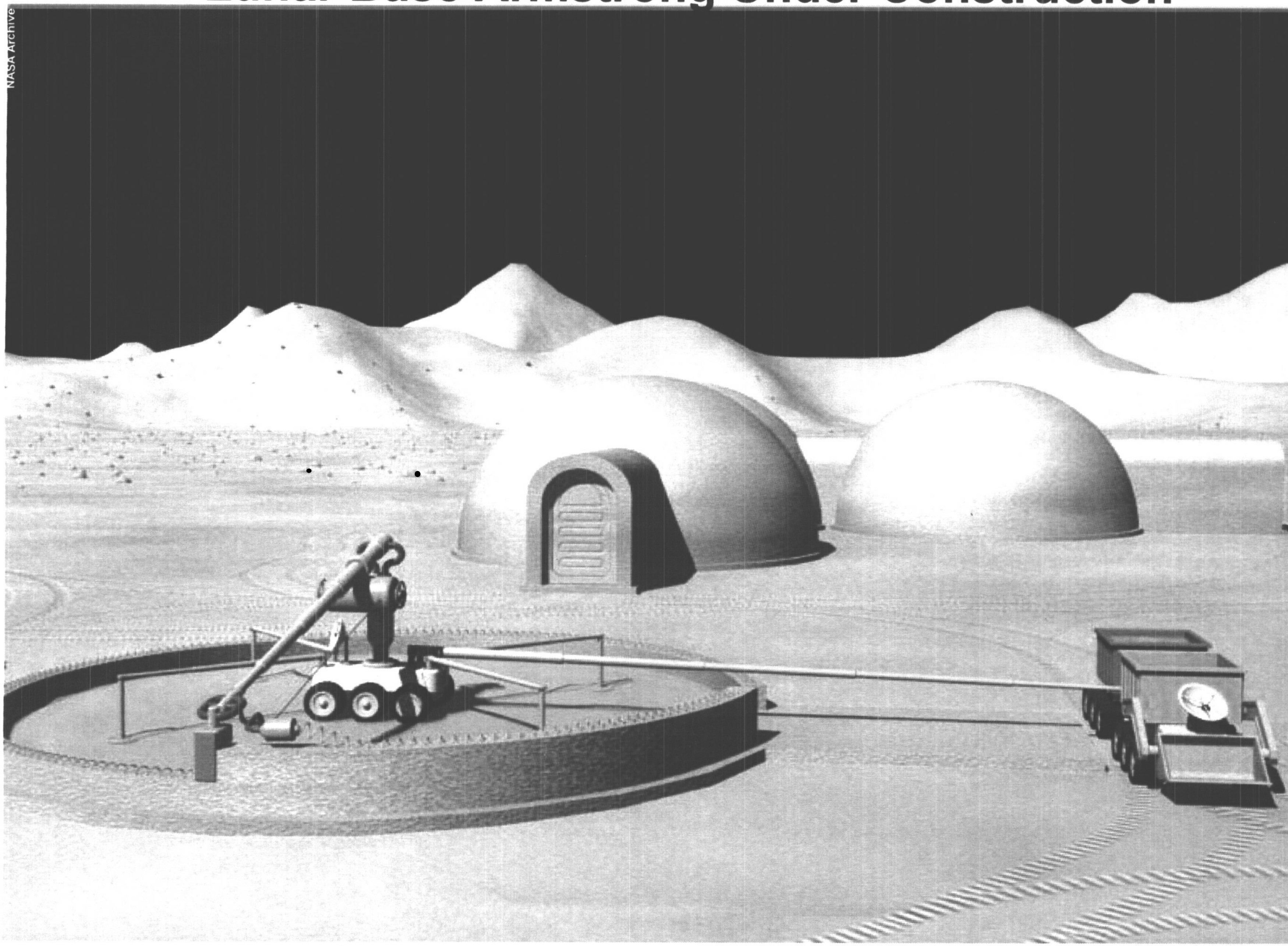
- Freeze/thaw effects on property integrity

- Thermal gradient effects

SSPO



Lunar Base Armstrong Under Construction



SSPO